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Abrasive Waterjet Cutting: Experiments on Hollow-Core Concrete Slabs

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ABRASIVE WATERJET CUTTING -
EXPERIMENTS ON
HOLLOW-CORE CONCRETE SLABS

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ABSTRACT

Waterjet and abrasive waterjet machining have successfully replaced traditional methods for a wide range of applications. Waterjets can cut virtually any material from asbestos brake-shoe linings to titanium components for the B-1 bomber. Researchers have even experimented with waterjets for osteopathic surgery. The potential for waterjet technology appears boundless.

This paper reviews past theoretical and experimental research on waterjet machining and identifies the current and potential applications in the construction industry. It then reports the results of a series of experiments conducted to further investigate the potential application of waterjet and abrasive waterjet machining in the processing of common construction materials such as concrete slabs. The experimental study was specifically aimed at optimizing the performance of abrasive waterjets in cutting hollow concrete slabs.

Specifically, the abrasive waterjet parameters which affect cutting hollow pre-stressed concrete slabs were investigated for their influence on cutting through the hollow core concrete slabs as well as the steel cables which lie at the bottom of these slabs. Five factorially designed experiments were included.

The most significant parameters found in the study were pressure, abrasive flow rate and number of passes, with the primary criterion for significance being depth of cut. As an additional criterion of significance, the kerf quality, while not "smooth," was examined for its sufficiency. Increasing each of the most significant parameters had a positive effect on depth of cut. The number of passes was by far the most significant parameter. A practical limit existed, however, beyond which increasing the number of

passes did not provide any significant gains in the resulting depth of cut. Found to be somewhat less significant parameters were stand-off distance, and traverse rate. Much less significant parameters were nozzle diameter and abrasive size and type. Nozzle angle was not studied.

Another limitation was that cutting the hollow concrete slabs from one side only was not sufficient to sever the blocks completely. To accomplish this (under the testing conditions), it was necessary to turn the blocks over and cut from the other side. While this was a relatively simple procedure, turning the blocks over to cut from both sides would require special fixtures for commercial application.

The overall study demonstrated that the abrasive waterjet technique does offer the potential for practical application in the construction industry. Although some operational barriers still exist, the experimental work clearly demonstrated that abrasive waterjet cutting can find specific applications with hollow core concrete slabs.

WATERJET AND ABRASIVE WATERJET MACHINING

For machining hard and brittle materials such as alloy steels, ceramics and concrete, conventional machining processes are impeded by the properties of these materials. Also, the geometry of the part to be produced may limit the application of conventional machining processes. Most of these hard materials cause severe tool wear in conventional machining processes. With non-traditional machining processes like waterjet and abrasive waterjet machining, tooling, cutting and finishing times can be reduced to increase productivity. It is now estimated that waterjet cutting is growing at a rate of 40% per year [1].

Equipment

The basic waterjet system consists of a water pump, filter, intensifier, tubing and swivels, a nozzle and a catcher as shown in figure 1. Abrasive waterjet systems require the addition of an abrasive hopper and feeder system. The materials for nozzles vary according to the type of jet to be formed and the type of abrasive mixing desired. Figure 2 shows a typical nozzle. Abrasive waterjets can be formed in two different ways. The first method consists of introducing the abrasive particles after forming the jet as shown in the figure. In the second method, the water and abrasives are mixed in a chamber first and then the jet is formed. Apparently the internal mechanics of these two chambers are not clearly understood as no clear explanation exists in the literature. Pressures can be generated up to 60,000 psi. The normal operating pressure ranges from 40,000 to 50,000 psi. The range of nozzle diameters is approximately from .003 to .020 inch depending on the application.

Waterjet Machining

In waterjet machining, a highly pressurized, high velocity jet of water strikes the surface of the workpiece. Hashish and DuPlessis [2] explain that the fracture of material involves a series of complex phenomena including compression, tension, shear, erosion, cracking, wave propagation, cavitation damage and wear. The dominant material removal mechanism is dependent on the type of load, the type of material and the feed rate. Hashish and DuPlessis have determined analytically the relationship between the parameters of a continuous jet and the workpiece material properties by adopting the following approach.

> A control volume was formulated to determine the effect of the waterjet on the target material.
>
> The hydrodynamic forces acting between the jet and the target were determined.
>
> Models were formulated to describe the stress-strain relationship of the target materials when subjected to the hydrodynamic forces.

The control volume (figure 3) surrounds the jet in the kerf. Within the control volume, friction on the side walls of the cut and the material's resistance to fracture resist the jet. The cutting process is analyzed by determining W, the velocity of the control surface into the material. Horizontal feed is approximated by a series of steps, with each step equal to the nozzle diameter.

A physical model of the process (figure 4) was developed by employing high speed photography on transparent plastic workpieces to confirm the cutting step theory. The cutting mechanism was mainly due to the compressive forces which fracture the material. As the cut deepens, the waterjet reaches a critical velocity where the forces are insufficient to fracture the material further and the cutting ends.

Continuity and momentum equations describe the forces that are applied on the target. Density changes due to frictional heating were neglected and the area of cut was assumed to remain constant to simplify the continuity equations. Similar assumptions were necessary to simplify the momentum equations. Refer to Hashish and du Plessis [2] for further details.

Material fracture by the high velocity waterjet depends on the time of application. Mechanical elements were modeled to simulate the time dependent response of target materials to the impact of the jet. For detailed explanation refer to Hashish and du Plessis [2].

Ultimately, the control volume analysis, hydrodynamic force analysis and resistance models led to the nondimensional equation relating the jet parameters, material properties and feed rate. The general cutting equation is

$$\frac{z}{d_n} = \frac{1 - \dfrac{\sigma_c}{\rho {v_1}^2}}{\dfrac{2c_f}{\sqrt{\pi}}} \left\{ 1 - e^{-\left(\frac{2c_f}{\sqrt{\pi}}\right)\left(\frac{\rho v_1}{\eta}\right)\left(\frac{v_1}{\mu}\right)} \right\}$$

where

z=depth of cut	v_1=jet velocity
d_n=nozzle diameter	c_f=friction coefficient
ρ=density of workpiece	η=damping coefficient
σ_c=compressive yield strength of workpiece	μ=traverse rate

The above equation describes the cutting mechanics for a wide range of materials, but can be adapted only after adjusting the appropriate model elements for different material resistance.

Material fracture occurs when the compressive forces exerted by the waterjet exceed the yield strength of the target material. As the cut deepens, the forces are insufficient to fracture any more material and cutting stops. The jet velocity and width are functions of the stand-off distance between the nozzle and the target material as shown in figure 5. Farther from the nozzle, the velocity decreases and the width increases. Since only a portion of the jet is effective in removing the material, it is important that the stand-off distance be such that the most effective portion of the jet impacts the workpiece.

Simple waterjets effectively cut such materials as plastic, asbestos, wood and soft rock. They lose effectiveness, however, when applied to harder and brittle materials like glass, hard rock, metals or ceramics. Some enhancement is necessary to apply this equation to the machining of hard and brittle materials.

Abrasive Waterjet Machining

Addition of abrasive particles enhances the waterjet's cutting ability. Now, there is a new cutting mechanism. Instead of exerting compressive forces on the work material, the water accelerates abrasive particles towards the material. The abrasive particles are introduced into the waterjet in one of the two methods which were described earlier. Abrasive waterjet cutting involves the same complex interaction of processes as "pure" waterjet cutting, but the process is even further complicated by the addition of the abrasive particles. Each abrasive particle "chips away" the target material. There are, in effect, thousands of tiny cutting edges, each fracturing away a small portion of work material. For metals, this is still a shearing process. For more brittle materials it is more like a tiny explosion with each abrasive particle displacing a piece of material.

Current Applications

Some of the materials successfully processed with waterjets include the following.

"Pure" Waterjet	*Abrasive Waterjet*
plastics	glass
asbestos	hard rock
wood	ceramics
soft rock	metals
food products	composites

Waterjet/abrasive waterjet technology offers several advantages over conventional methods of machining these and other materials. With asbestos, for example, waterjet machining results in very little dust, hence a reduced health risk. Using abrasive waterjets on metals generates no heat. Steel, therefore, can be cut with no risk of a heat affected zone which may be undesirable. Composites which are cut with abrasive waterjets have relatively smooth kerfs with no frayed edges.

LITERATURE REVIEW

The experimental studies of waterjet machining covered in this section span a period of almost twenty years. Clearly, then, the knowledge of the process is not new although many applications are.

McCurrich and Browne [3] divide the parameters that control waterjet cutting into two groups: the power group and the efficiency group.

Power Group	*Efficiency Group*
jet pressure	stand-off distance
flow rate	jet interference
nozzle size	nozzle shape
	water additives

The effects of these parameters vary according to the material that is being cut. Other parameters include traverse rate, number of passes, type of jet (continuous or pulsating), and the characteristics of the abrasives that are used for abrasive waterjets.

A brief list of criteria for evaluating the parameters includes:

material removal rate
kerf quality
environmental effects
power/energy requirements
penetration depth

The importance of any of these criteria depends on the application. In demolition work, for example, the kerf quality is unimportant while material removal rate may be the critical factor.

Brook and Page [4] found that the energy required to fracture rock specimens by waterjet decreases with increasing traverse speed of the jet relative to the specimen. They also discovered that most of the penetration occurs in the first fraction of a second of application, while continued application of the jet does not increase the depth of penetration. With increasing jet pressure, they reported an increase in removal efficiency. Jet performance predictions such as those formulated by Hashish are not easily related to rock properties. Finally, the best efficiency occurs when jet interference is avoided. Jet interference occurs when the used portion of the jet and the removed pieces of work material remain in the kerf, thus impeding the action of the new portion of the jet.

Labus [5] reports that for stationary targets, the specific energy required decreases with increased jet pressure. For traversing targets, higher pressures yield a higher optimum traverse rate. Accordingly, the most effective application would consist of a rapidly traversing, high pressure jet. An important note, however, is that the energy efficiency decreased in Labus's tests as the kerf depth increased. He determined that the jet-wall interaction causes the efficiency to decrease. This is a problem similar to that found by Brook and Page [4] who report that jet interference affects penetration. In order to improve the process, some means must be provided to draw away the "used portion" of the waterjet and the resulting debris.

Conn, Gracey, Rosenburg and Gauthier [6] used a foam rubber seal and pumping system to contain the jet and debris in tests of a system for pavement cutting. Adapting this type of system for other applications would minimize the deleterious effects of jet interference within the kerf.

Hurlburt, Crow and Lade [7] identified four rock properties and two jet parameters that are essential to explain the rock cutting mechanism. The rock properties are permeability, porosity, strength and grain size. The jet parameters are jet pressure and diameter. They found that permeability is the most important rock property which affected jet cutting. A wide variation in permeability did not, however, lead to a correspondingly high variation in slot depth. The depth of slot depended linearly on the jet parameters, particularly jet pressure. A critical pressure existed below which no cutting occured. Depth of cut and quality of cut both decreased with increasing feed rate.

Rehbinder [8] also found that permeability was the most significant factor which affected the "erodability" of rock. He also determined that depth of slot was a function of: jet pressure and diameter, rock grain size and permeability, and the time of exposure. Rehbinder's model of the process was fairly simple to explain. Water penetrated the voids between the rock's grains and when the resulting hydraulic pressure exeeded the cohesive forces, the rock eroded. This model was consistent with the conclusion that permeability is the most significant factor.

Nittinger [9] reported the use of waterjets for repairing bridges. The methods, developed in Switzerland, easily removed damaged concrete without affecting the steel rebars. The basic principle behind the method was fairly simple. Water was forced into the cracks and air voids in the concrete. Once the voids were filled with water, the continued application of the jet forced the concrete to fracture. Since no abrasives were used, the reinforcement bars were not damaged.

Summers and Henry [10] have outlined four controllable factors for waterjet rock cutting. These were: jet pressure, nozzle diameter, traverse speed, and number of passes. They reported a sharp drop in cutting efficiency with increasing jet pressure, but an increase in efficiency with increasing traverse speed. The conclusion that cutting efficiency decreases with increased jet pressure does not agree with other researchers' reports. Results reported by Harris and Mellor [11] and Brook and Page [4] support the conclusions that efficiency increases with a jet pressure increase as reported in [4] [5] [12]. An important part of the work by Summers and Henry is the consideration of a combination of systems for rock breakage. They used waterjets to make the initial slots followed by mechanical breakers to remove the remaining ribs of material. This two phase method proved to be better than using waterjets alone.

Hamada, Fukuda, and Sijoh [13] explained the effects of waterjets as a function of jet parameters. They have determined the existence of optimum stand-off distance and traverse rate. Additionally, they tried to improve the waterjet performance by using a water additive. Specifically, the experiments indicate that the specific energy required can be defined as

$$\text{specific energy} = \frac{\text{jet power consumption}}{\text{material removal rate}}$$

for a given pressure, nozzle diameter, and standoff distance. Depth of cut was found to increase with decreased traverse velocity and increasing jet pressure.

Addition of polyethylene oxide improved the waterjet's cutting performance. Actual depth of cut increased by as much as two times versus plain waterjet, but at higher specific energy levels. Brook and Summers [12] also reported some advantages resulting from the use of polyethylene oxide. The increased effect is due to cohesion of the jet which is increased by the additive and hence the penetrating power is enchanced.

Olsen [14] considered the problem of cutting concrete containing aggregate. He found that high traverse speed suffices to cut all but the aggregate, but at low speeds, a poor quality kerf results. Therefore, he had to search experimentally for an optimum traverse rate that would cut both the concrete and the aggregate while still maintaining a desirable quality of cut. As others, Olsen found that multiple passes yield the best results.

Arasawa, Matsumoto, Yamaguchi, and Sumita [15] determined the relationship of stand-off distance and nozzle traverse rate to depth of cut in concrete. They found that depth of cut is linearly proportional to stand-off distance and proportional to the logarithm of traverse rate. Also, they found it to be more efficient to remove the concrete first and later to cut the bars in steel reinforced concrete. The reason for this is that the energy for cutting the steel bars is about twenty-seven times that required for cutting the concrete.

Puchala, Lechem, and Hawrylewicz [16] have reported on an automated system for mass removal of concrete. Specifically, they determined the effects of jet geometry and kinematics, aggregate size and cement mix structure on the cutting efficiency. Cutting efficiency in this case was measured by average depth of cut, cutting capacity or volume removal rate, and specific energy expended. The conclusions were that higher productivity and reduced specific energy are favored by higher pressure and maximum traverse speed of the nozzle.

The cement mix properties were also examined. Cracking can be a problem because the compressive strength of most aggregate is greater than that of the overall mix. The waterjet, therefore, will attack the boundary between the mix and the aggregate rather than cutting directly through the concrete in a controlled fashion. This does not matter if kerf quality is relatively unimportant compared to material removal rate as in the application studied by the researchers. Of course, for other applications, kerf quality is much more important, so the problem of cutting through the aggregate must be resolved.

Hashish [17] has presented a plan for optimizing the performance of abrasive waterjet cutting. He suggest that the level of each parameter has its own advantages and disadvantages that must be considered when selecting its level or value. Overall optimization will require quantitative models of the cutting process itself, the abrasive-water mixing process, as well as the economics of the abrasive waterjet process. Only the cutting process, however has been modeled so far. Ultimately, Hashish concludes that a better understanding of the physical model and the development of predictive models are necessary before complete optimization can be achieved.

Besides depth and removal rate, kerf quality is also important. Tan [18] discusses a model for surface finish achievable with abrasive waterjets. The striated surface finish, characteristic of abrasive waterjets, is one that is common to other single stream cutting techniques such as laser cutting. The striations are caused by the geometry of the process rather than by the dynamics of the process (such as jet instability) as one might think. Tan's model does not require detailed knowledge of all the parameters affecting cutting. Instead, it uses first order approximations to predict the quality of cut obtainable as related to pressure, traverse velocity, and grit size.

A brief summary of the basic parameters and their effect on depth of cut (a common measure of effectiveness) are as follows.

Parameter	*Effect on Depth of Cut*
Pressure	Approximately linear Minimum critical value exists
Nozzle Diameter	Initially linear Minimum critical value exists
Traverse Rate	Complex function
Abrasive Particle Size	Unclear effect
Abrasive Flow Rate	Initially linear Higher flow rates may reduce depth
Number of Passes	Multiple passes generally improve results
Stand-Off Distance	Depth of cut decreases with increasing stand-off
Abrasive Hardness	No effect beyond a certain limit

CONSTRUCTION APPLICATIONS

Short Range

The immediate application of abrasive waterjet process requires study of the process parameters to optimize the material removal rate while still maintaining an acceptable kerf quality. This would help in making the abrasive waterjet process more economical.

Additionally, the abrasive waterjet cutting should be applied to construction materials other than prestressed concrete. It has already been demonstrated by Hashish and others that the abrasive waterjets can successfully cut steel, rock and composites. The process has to be refined so that it can be applied to cut these types of materials as they are used in the construction industry.

It has already been shown that the abrasive waterjet process can effectively be carried out with portable equipment by Conn. Similar equipment configurations can be developed for on-site applications such as excavation of new sites, demolition of existing structures or making finish cuts.

Long Range

Abrasive waterjet may be coupled with construction robots, automatic material handling and inspection equipment for automating the cutting process in the construction industry. The benefits of such automation will include reduced manpower, increased productivity, greater safety and repeatable performance.

Application to Concrete Slabs

Concrete slabs are basic construction materials, and accordingly, an appropriate area for waterjet technology to be used in the construction industry. *High Concrete Structures, Inc.*, a manufacturer of pre-stressed concrete slabs has an interest in adapting a waterjet system as an alternative method of sectioning and forming holes in concrete slabs.

Processing takes place in two stages. First, the slabs are cast 4 feet wide and thicknesses range from 6 to 12 inches (in 2 inch increments). The long slabs are cut into smaller sections with diamond tipped saws. These cuts are all straight cuts directly across the width of the slabs. Holes or pockets, if required, are formed by hand. In the second stage, any additional cuts are made; again with diamond saws. These second cuts may be straight as in its first stage, or angled cuts.

Excessive tool wear and the expense of diamond saws led to the possible application of waterjets as an alternative process. Determining the applicability of waterjet technology to the processes at *High Concrete* is the specific short term research goal. The long term goal is to adapt waterjet/abrasive waterjet systems to a variety of applications in the construction industry. The abrasive water jet system, as developed for *High Concrete* would be an appropriate candidate for construction automation as the system is easily programmable once the parameters have been selected. Moselhi [19] points out the potential for robotics and automation in the construction industry. Among his conclusions are the following:

1. The construction industry is the largest industry in many countries.

2. The potential of robotics in building construction (which represents over two-thirds of the total volume of construction in North America) is promising.

3. A number of challenges still exist before effective implementation of the construction robot can be made.

4. Partial automation should be considered by using existing robots for simple construction tasks and by introducing further automation of existing equipment.

5. Further research is needed in the area of construction automation and robotization.

INITIAL EXPERIMENTAL PROGRAM

Several factors have been identified which determine the effectiveness of abrasive waterjet cutting. Some experimental work is necessary to determine the optimum values of these parameters for the processing of concrete slabs. Specifically, we wish to identify the parameters that have the largest effect on the resulting cut and the values that yield the best results. Since the number of factors is large, a fractional factorial experiment is appropriate. The parameters of interest are:

Pressure
Nozzle Diameter
Traverse Rate
Abrasive Flow Rate
Number of Passes
Stand-Off Distance
Nozzle Angle
Abrasive Size

The responses which are of interest include depth of cut, kerf quality (tolerance) and material removal rate. Depth of cut has already been investigated in some detail. Kerf quality is perhaps a more important criterion for the short term goal of adapting an abrasive waterjet system for the concrete slab processes at *High Concrete.*

For the above eight parameters, 256 experiments would be necessary for a full factorial experiment with each factor at 2 levels. Obviously, a smaller scale experiment is necessary for a preliminary investigation. The fractional factorial experimental design requires considerably fewer experimental runs and provides enough information to determine the factors that should be studied more thoroughly in future experiments. A range of values for some of the 8 factors is listed in Table 1. These served as a guide in choosing the experimental values to be used. The actual levels of each parameter were determined by the capabilities of the available equipment and with the advice and knowledge of those experienced with the equipment and its capabilities.

The purpose of experimentation was to determine the effects of the eight parameters on the resulting cut and to determine the optimum values for the significant parameters.

Because of the limitations of the available equipment, nozzle angle could not be changed from the standard position of 90°. The nozzle is permanently mounted perpendicular to the table that hold the concrete blocks. The remaining variables, however, were adjustable. In order to accommodate a preliminary investigation of the parameters, a fractional factorial design, specifically a $\frac{1}{4}$ fraction of a full 2^7 was performed. Details of the experiments are given in the following pages.

Original Experimental Design

Fractional factorial design is useful to determine the parameters that have significant effects. This method allows quick identification of the significant factors that need to be investigated further. The alternative would be to run an exhaustive experiment or set of experiments to measure the effects of all the possible combinations of variables. Obviously, such an approach would be extremely time consuming and prohibitively costly.

The initial experiments included each of the 7 variables at two levels (high and low) each. Table 2 lists the variables and their corresponding values. Only garnet abrasive was used in the initial experiments.

Experimental Design

In discussing the experimental design, the following nomenclature applies. A, B, $\cdots$, G identify the 7 parameters as in Table 2. a, b, $\cdots$, g identify the value (high or low) of a parameter. If the identifier appears in a particular combination of parameters, or run, then the factor is at its high level; otherwise it is at the low level. For example acg represents the run with factors A-nozzle diameter, C-pressure and G-stand-off distance at their high values while the remaining parameters are at their low values. The complete experimental design is presented in Table 3.

In Table 3, the effects column indicates which main effect (A-G) or interaction effect is measured by that particular combination. The order column simply indicates the sequence of the runs. For valid results, the runs must be in random order.

Figure 6 shows the sample blocks and the direction of cut. Points 1 and 2 are the entrance and exit points respectively for the abrasive waterjet. The depth of cut (d) is measured at each of these points and included in the experimental design table.

Data Analysis

The following assumptions underly the factorial design analysis.

1. The data are normal.
2. 3 way and greater interactions are negligible.
3. The runs were completed in random order.

Because of time limitations, the runs could not be run entirely in random order. Changing grit and nozzle are both relatively long operations compared to the time required to change any of the other variables. In order to compensate for this, the runs were divided into four "blocks" and the runs within each block were in random order as illustrated in Table 4.

Using this approach required only one grit change and two nozzle changes. Of course the complete randomization principle has been violated. The violation, however, is not significant if the "block" effect is not statistically significant.

Data Analysis - Experiment One

The sum of squares analysis (see Table 5) for depth of cut indicates that the most significant factors are passes, abrasive flow rate and pressure. The nozzle-grit interaction is also significant. The individual contribution of each factor (grit or nozzle), however, is not revealed due to the "blocking" arrangement described previously. In the first experiment, standoff distance was hard to maintain at the prescribed levels of .100 inch and .200 inch because the concrete blocks were not perfectly level. In any event, within the constraints of this limitation, the measured effect of standoff distance on depth of cut was negligible. Further, the results suggest that slower traverse rate, smaller grit size and smaller nozzle diameter are favorable for increasing depth of cut although the significance of these factors as measured by their sum of squares values is much less important than the effects of increasing the number of passes, faster abrasive flow rate and higher water pressure.

In addition to the numerical analysis, plots of the depth of cut versus each individual parameter confirm the effects. Figure 7 graphically shows the effects on depth of cut by increasing each of the seven parameters in Experiment One. Each plot shows the average depth for each parameter at its respective low and high levels. The slope of the line connecting the two points indicates the degree to which increasing or decreasing the value of the particular parameter will affect the depth of cut. A positive slope indicates that increasing the parameter has a positive effect (i.e. deeper depth), while decreasing it has a negative effect (i.e. more shallow depth).

From the plots of figure 7, it is clear that for a better response or deeper cut, it would be favorable to increase pressure, abrasive flow rate and the number of passes, but to decrease nozzle diameter, grit size and traverse rate. Changing the standoff distance has no measurable effect.

Of course the plots of figure 7 are presented for only the main effects without considering the interactions. These interactions or combinations of factors must be examined as well. Relying upon the main effects alone could be misleading. For example, it appears from figure 7 that increasing either nozzle diameter or grit size will result in decreased depth of cut. This conclusion, however, does not consider the possibility that the interaction of these two factors may influence the depth of cut as well. For further details regarding the two way interaction and their effects on depth of cut, please refer to reference [20]. Examination of these plots reveals that the general trends suggested by the parameter effects in figure 7 are not contradicted by any of the two way interactions. Using the nozzle-grit size interaction as an example, it is clear that the combination of smaller grit and smaller nozzle is preferable for the best response (deepest cut). The plot also shows how to choose parameter values under specific constraints. If, for example, only a large nozzle is available, but there is a choice of grit sizes, then the larger grit should be chosen (assuming all other conditions remain constant).

The important goal of the current research is to determine an optimum, predictable response. In other words, given a desired depth of cut, it is necessary to determine the required parameter settings. The first step towards that goal is formulating a simple linear regression to see how well the actual depth of cut can be predicted. From the previous analysis, it is reasonable to drop standoff distance, grit size and nozzle diameter from the regresssion analysis. The regression results are listed in Table 6. This analysis yields the following equations:

$$\hat{z}_1 = -5.73 + .14P - .04f + 1.75\,v + .351n$$

$$\hat{z}_2 = -6.13 + .13P - .01f + 2.06\,v + .41n$$

where

$\hat{z}_m$	=	depth of cut
P	=	pressure (ksi)
f	=	traverse rate (inch/min)
v	=	abrasive flow rate (lb/min)
n	=	number of passes

The actual measured depths and their corresponding predicted values are listed in Table 7. Obviously, the model is inadequate for practical purposes.

FURTHER EXPERIMENTATION

The original experiments identified the significant factors among the original seven that were examined and their effects. Accordingly, the next logical step is to investigate further the significant parameters with the goal of optimization in mind.

Given the results of the first experiment, new experiments were designed to further investigate the significant factors. Four new experiments were planned as

Experiment Two

A duplicate of the first experiment, but with iron grit rather than garnet abrasive. The purpose of this design was to compare the effectiveness of iron grit versus garnet.

Experiment Three

A full factorial experiment using the signifcant parameters identified in the first experiment. In this case, the response was number of passes required to cut through the concrete blocks. This response was chosen because none of the concrete blocks in the first experiment were cut through and severed into two pieces. In fact, the deepest cut in the first experiment was only approximately 4 $\frac{1}{4}$ inches while the sample blocks were 8 inches deep. Accordingly, the number of passes was used as the new response. Obviously, then, the goal in this case was to minimize the number of passes.

Experiment Four

None of the cuts in the first experiment could successfully cut through the blocks. In fact, none of the cuts were deep enough even to reach the steel cables at the bottom of the blocks (see figure 6). Therefore, Experiment Four was planned to determine the effectiveness of cutting through the steel cables. The plan to accomplish this was as outlined below.

I. With iron grit
    1. cut from top until one-half way through

2. record number of passes
   (record depth if not one-half way through)
3. turn the block over, cut the same slot until it is cut completely
   (record depth if not cut completely through)

II. Repeat I with garnet

Experiment Five

In this final experiment, only the most significant factors as identified in the first experiment were varied. Pressure, traverse rate and abrasive flow rate were varied at three levels for a full factorial (3^3) design. The response was depth of cut.

Data Analysis - Experiment Two

Experiment Two could not be conducted entirely as planned. The original purpose of the second experiment was to duplicate the first experiment, but garnet was replaced with Iron grit. The motivation for this was to allow the comparison of the two grit types since this factor was omitted in the original experimental design. Unfortunately, the iron grit could not be found in two separate sizes comparable to the two sizes of garnet abrasive used in the first experiment. The iron grit was available in a "mix" of sizes from 80 to 120 mesh size (IG80 - IG120). The experimental plan was altered as shown in Table 8.

Note that standoff distance was no longer considered as a variable. As mentioned in the discussion of the first experiment, maintaining the two distinct values for standoff distance was unreliable. Therefore, in the second and all subsequent experiments, standoff distance was held "constant" at .150 inch.

The sum of squares analysis for Experiment 2 (Table 9) indicates that the most significant factors affecting depth of cut are number of passes, abrasive flow rate and traverse rate. Passes and flow rate have positive effects on depth of cut while traverse rate has negative effect. These results are consistent with the first experiment results. Tables 10 and 11 present the regression results and depth of cut predictions for Experiment Two.

The prediction equations are:

$$\hat{z}_1 = -3.42 + 7.21\ d_n + .08\ P - .10\ f + 1.18\ v + .81\ n$$

$$\hat{z}_2 = -4.90 + 6.01\ d_n + .12\ P - .09\ f + .93\ v + .73\ n$$

where

$\hat{z}_m$ = depth of cut

d_n = nozzle diameter

P = pressure

f = traverse rate

n = number of passes

v = abrasive flow rate

The predicted values are within $\frac{1}{4}$ inch of actual depth in 50 % of cases and within $\frac{1}{2}$ inch in 75 % of the cases.

Data Analysis - Experiment Three

The parameters for Experiment Three are listed in Table 12. For this set of experiments, the response was number of passes to cut through the concrete blocks.

Unfortunately, none of the runs could successfully sever the blocks. During the course of the experiment, therefore, the response was changed from number of passes to cut through to number of passes to reach the steel cables.

The sum of squares table for the third experiment is presented in Table 13. From this analysis, the most significant effects are abrasive flow rate, pressure and traverse rate. Abrasive flow and pressure have negative effects while traverse rate has a positive effect on the response. Since the response is the number of passes required, these results are consistent with the previous findings. The nozzle diameter and grit type have insignificant effect on the response. It is to be noted that the quality of the cut appears somewhat better for iron grit than for garnet. These results suggest that a closer examination of the difference between garnet and iron grit abrasive type is warranted.

Data Analysis - Experiment Four

The parameters for Experiment Four are listed in Table 14. The procedure for this experiment was as follows.

I. With iron grit
   1. cut from top until one-half way through
   2. record number of passes
      (record depth if not one-half way through)
   3. turn block over, cut the same slot until the cut is completely through
      (record depth if not cut completely through)

II. Repeat I with garnet

The results were as follows:

G120 (garnet grit) 7 total passes required -- 3 from top; 4 from bottom cutting through the center after third pass from top

first pass from bottom cuts the concrete up to the rebars

second pass slightly cuts rebars

on third pass (and fourth) traverse reduced to 10 in/min at rebars

third almost cuts completely through

fourth pass completely severs block

IG80 (iron grit) 7 total passes required -- 3 from top; 4 from bottom

third pass from top not quite half way at d_1; well past at d_2

reduce the traverse as with G120 at rebars on cuts from the bottom

completely cut through on fourth pass from bottom (7^{th} total pass)

No statistical analysis was done for this experiment as only two samples were cut. A qualitative analysis is appropriate, however, and is included in the discussion of the photographs in another section.

Data Analysis - Experiment Five

The parameters for Experiment Five are listed in Table 15. The sum of squares results are presented in Table 16 and the regression results are given in Table 17. The sum of squares analysis is not quite so straightforward for the fifth experiment as for the first, second and third experiments. Since the full factorial design at three levels complicates the analysis, a more clear view of the effects is measured through the use of response surface graphs. Figure 8 presents the overall effects of the three parameters: pressure, abrasive flow rate and number of passes. From the graphs, it can be realized that all three parameters have a positive effect on depth of cut. Additional graphs showing the interaction effects can be seen in [20]. These graphs support the conclusions derived from figure 8. Additionally, they demonstrate that the effect of increasing the pressure is less for faster flow rate than for slower flow rate. The effect of increasing the flow rate is more noticeable at higher pressure or with increased number of passes. Finally, the effect of increasing the number of passes varies little with varying levels of abrasive flow rate or pressure. Overall, Experiment Five has demonstrated that increasing the number of passes has the greatest effect on depth of cut. After a point, however, the performance increase (greater depth) trails off with additional passes. The greatest amount of cutting is done by the early passes while later passes result in small marginal gains in depth regardless of the other two parameter values. Consider the two cases: A- high pressure and abrasive flow rate, B- low pressure and abrasive flow rate. The initial depth in case A is greater than that for case B for the first few passes. After subsequent passes, however, increasing the number of passes further will have no more effect on additional depth of cut in case A than in case B.

SIGNIFICANT RESULTS DEMONSTRATED BY PHOTOGRAPHS

Appendix A contains photographs of some of the sample concrete blocks that were cut during the present study. These photographs illustrate the effects of the various parameters on the depth of cut and kerf quality.

The cuts from the first experiment demonstrate the importance of the number of passes on depth of cut. Cuts 1, 13 and 28 are deeper cuts than the others shown in photograph #1. The only parameter that was different for these two sets of cuts (1, 13, 28 versus 2, 11, 12, 14, 27) was the number of passes, with the first group having 4 passes while the second group had 2 passes. Photograph #2 shows cuts 27 and 28 in closer detail. Cut 28, with the larger number of passes is still deeper than cut 27 despite the slightly higher pressure and higher abrasive flow rate for cut 27. All other parameters were the same for these two cuts.

The samples from the third experiment show that the least number of passes is required for high pressure and slow traverse rate. Cuts 9 and 10 (both at low pressure) required 15 and 19 passes respectively, to cut as deep as to the steel cables. Cut 9 was at fast traverse and slow flow rate, while cut 10 was at slow traverse and high flow rate. Cuts 15 and 16 (both at low traverse rate and high pressure) required 21 and 8 passes respectively to reach the steel cables. Cut 15 was at slow flow rate and cut 16 was at high flow rate. The best performance among these runs was cut 16 (high pressure, slow traverse rate, high abrasive flow rate). The appearance of cuts 15 and 16 is not much different. The significant difference is that cut 16 required only eight passes while cut 15 required nearly three times as many passes.

The samples from experiment five show that breakthrough at the bottom of the samples only occurs with the largest number of passes regardless of pressure or abrasive flow rate. Examining cuts 1-4 as compared to cuts 21-24 reveals that better depth is obtained at higher pressure. Cuts 1-4 (at higher pressure) have broken through the bottom. But for cuts 21-24, only 23 and 24 have slightly broken through. Note that these two cuts resulted from the higher number of passes (6 and 4 passes respectively). This demonstrates further the importance of number of passes on depth of cut. With other parameters at less favorable levels, the depth of cut is still increased if the number of passes is increased sufficiently. Of course, there are some limits as discussed previously. Beyond a certain point, even increasing the number of passes results in little additional gain in the obtainable depth of cut.

FUTURE WORK

Before abrasive waterjet cutting can be applied to applications in the construction industry, additional work and refinement are necessary. Some of the limitations have already been mentioned in the previous sections. Specifically, the parameters affecting depth of cut must be optimized so that a predictable, controllable response is possible. Additionally, some method must be developed to allow cutting through the steel cables. As demonstrated in Experiment Three, these cables can be cut successfully by the abrasive waterjet. The concrete blocks, however, had to be turned over to accomplish this task. While this was a simple procedure in the present investigation with small samples, special fixtures have to be developed to accomplish the same task in industry with full sized concrete slabs.

One factor which was not included in the current research was nozzle angle. This was omitted because the equipment that was used did not have the provision for adjusting the nozzle position. Including this factor in future research may show that an increase in kerf quality or depth of cut is possible by changing the position of the abrasive waterjet relative to the concrete surface.

Other possibilities include investigating the effect of cutting with multiple nozzles or using different types or sizes of abrasive grit. Multiple nozzles could possibly be arranged so that two nozzles are used to accomplish cutting from both sides of the concrete slabs at the same time. Another configuration could involve cutting with two or more nozzles in sequence. The benefit of this arrangement is that several cuts could be made, but in less time than with one nozzle making repeated passes. Any change in the number or configuration of nozzles would be a long term project and would require consultation with the equipment manufacturer.

Table 1. Guidelines for Parameters

Parameter	Investigator Conn et al [6]	Echert et al [16]
nozzle diameter (in)	.08-.141	.03
pressure (ksi)	1-15	14.5
flow rate (lb/sec)	n/a	.011-.11
traverse rate (in/min)	7-15	.06-.28
nozzle angle	90°, 85 °, 70°	n/a

Table 2. Parameters for Experiment One

one quarter fraction of a 2^7

Parameters	low	high	
A nozzle diameter	.03	.043	inches
B grit size	120	100	mesh
C pressure	45	48	ksi
D traverse rate	10	20	inch/min
E abrasive flow rate	.32	.64	lb/min
F number of passes	2	4	
G standoff distance	.1	.2	inch

"The grit used was garnet."

Table 3. Experimental Design - Experiment One

run	order	effect
(1)	3	---
afg	9	A
bfg	28	B
ab	20	AB+CF+DG
cf	1	C
acg	11	AC+BF
bcg	26	BC+AF
abcf	21	F
dg	5	D
adf	15	AD+BG
bdf	25	BD+AG
abdg	19	G
cdfg	6	CD+FG
acd	14	-
bcd	31	-
abcdfg	17	DF+CG
e	2	E
aefg	13	AE
befg	32	BE
abe	23	-
cef	7	CE
aceg	10	-
bceg	27	-
abcef	22	EF
deg	8	DE
adef	16	-
bdef	30	-
abdeg	18	EG
cdefg	4	-
acde	12	-
bcde	29	-
abcdefg	24	-

Table 4. Allocation of Runs for Experiment One

BLOCK	GRIT	NOZZLE	RUNS
one	120 mesh	.030 in.	1-8
two	120 mesh	.043 in.	9-16
three	100 mesh	.043 in.	17-24
four	100 mesh	.030 in.	25-32

Table 5a. Sum of Squares for Entrance Depth - Experiment One

A nozzle diameter
B grit size
C pressure
D traverse rate
E abrasive flow rate
F number of passes
G standoff distance

run	effect	depth	effect	sum of squares
(1)		2.20	4.435	157.3538
abcf	F	2.73	0.70125	3.934012
ab	AB,CF,DG	1.98	0.63875	3.264012
e	E	2.29	0.5625	2.53125
abcef	EF	4.35	0.48125	1.852812
cf	C	3.29	0.425	1.445
adef	ADE	2.04	-.41625	1.386112
abdeg	EG	1.26	0.37625	1.132512
dg	D	1.38	-.3525	0.99405
bdf	BD,AG	1.29	-.3525	0.99405
bfg	B	1.81	-.2975	0.70805
bdef	BDE	2.04	-.2325	0.43245
aefg	AE	2.92	-.21875	0.382812
afg	A	.85	-.21125	0.357012
abcdefg	ABCDE	2.51	-.19875	0.316012
befg	BE	3.17	-.19	0.2888
bcde	BCDE	1.23	-.185	0.2738
aceg	ACE	1.98	0.18125	0.262812
acd	ACD	1.92	-.17875	0.255612
cdfg	CD,FG	2.13	-.1725	0.23805
bceg	BCE	1.94	0.1675	0.22445
acg	AC,BF	1.98	0.16125	0.208012
abcdfg	DF,CG	2.10	-.14625	0.171112
abe	ABE	1.54	0.11125	0.099012
cef	CE	3.42	-.08	0.0512
cdefg	CDE	4.27	0.075	0.045
deg	DE	3.35	-.0525	0.02205
acde	ACDE	1.67	0.02875	0.006612
abdg	G	1.79	-.02375	0.004512
bcg	BC,AF	1.85	-.0075	0.00045
adf	AD,BG	2.17	-.00625	0.000312
bcd	BCD	1.51	-.0025	0.00005

Table 5b. Sum of Squares for Exit Depth - Experiment One

A nozzle diameter
B grit size
C pressure
D traverse rate
E abrasive flow rate
F number of passes
G standoff distance

run	effect	depth	effect	sum of squares
(1)		1.48	3.713125	110.2983
abcf	F	2.35	0.819375	5.371003
e	E	1.70	0.659375	3.478203
ab	AB,CF,DG	1.42	0.628125	3.156328
cf	C	2.23	0.381875	1.166628
befg	BE	2.10	-.20187	0.326028
abe	ABE	1.92	0.201875	0.326028
abdeg	EG	1.67	0.201875	0.326028
abcdefg	ABCDE	2.79	-.19187	0.294528
adef	ADE	1.73	-.18437	0.271953
bfg	B	1.42	-.17312	0.239778
aefg	AE	2.23	-.15687	0.196878
afg	A	1.23	-.14562	0.169653
aceg	ACE	2.1	-.14562	0.169653
bcde	BCDE	1.54	0.144375	0.166753
bceg	BCE	1.38	-.12812	0.131328
bcd	BCD	0.73	0.125625	0.126253
abcdfg	DF,CG	2.48	0.121875	0.118828
dg	D	1.04	-.10937	0.095703
acd	ACD	1.17	0.100625	0.081003
bcg	BC,AF	1.35	-.09937	0.079003
adf	AD,BG	1.67	-.09062	0.065703
bdef	BDE	1.92	0.080625	0.052003
cdfg	CD,FG	2.13	-.06562	0.034453
abcef	EF	2.67	0.048125	0.018528
abdg	G	0.79	0.045625	0.016653
cef	CE	3.85	0.038125	0.011628
cdefg	CDE	3.67	-.02687	0.005778
acde	ACDE	1.17	-.02312	0.004278
acg	AC,BF	1.15	0.020625	0.003403
deg	DE	2.54	-.00562	0.000253
bdf	BD,AG	1.79	-.00312	0.000078

Table 6. Regression Results - Experiment One

Regression Output: ENTRANCE DEPTH

Constant	-5.73611			
Std Err of Y Est	0.693653			
R Squared	0.406511			
No. of Observations	32			
Degrees of Freedom	27			
	pressure	traverse	flow	passes
X Coefficient(s)	0.141601	-0.03514	1.754760	0.351074
Std Err of Coef.	0.081747	0.024524	0.766386	0.122621

Regression Output: EXIT DEPTH

Constant	-6.13113			
Std Err of Y Est	0.487022			
R Squared	0.612406			
No. of Observations	32			
Degrees of Freedom	27			
	pressure	traverse	flow	passes
X Coefficient(s)	0.127604	-0.01102	2.056884	0.410156
Std Err of Coef.	0.057396	0.017218	0.538088	0.086094

Table 7. Depth of Cut - Experiment One

Entrance Depth		Exit Depth		
Experiment	Predicted	Experiment	Predicted	
z_1	$\hat{z}_1$	z_2	$\hat{z}_2$	run
2.19625	1.548183	1.4775	0.979335	(1)
0.8525	2.250332	1.2275	1.799648	afg
1.8125	2.250332	1.421875	1.799648	bfg
1.9775	1.548183	1.415	0.979335	ab
3.29	2.675136	2.2275	2.182460	cf
1.9775	1.972988	1.149375	1.362148	acg
1.8525	1.972988	1.3525	1.362148	bcg
2.7275	2.675136	2.3525	2.182460	abcf
1.38375	1.196738	1.04	0.869101	dg
2.165	1.898886	1.665	1.689414	adf
1.29	1.898886	1.79	1.689414	bdf
1.79	1.196738	0.79	0.869101	abdg
2.13375	2.323691	2.13375	2.072226	cdfg
1.915	1.621542	1.165	1.251914	acd
1.50875	1.621542	0.7275	1.251914	bcd
2.1025	2.323691	2.4775	2.072226	abcdfg
2.29	2.109707	1.69625	1.637539	e
2.915	2.811855	2.2275	2.457851	aefg
3.165	2.811855	2.1025	2.457851	befg
1.54	2.109707	1.915	1.637539	abe
3.415	3.236660	3.8525	2.840664	cef
1.9775	2.534511	2.1025	2.020351	aceg
1.9375	2.534511	1.375	2.020351	bceg
4.3525	3.236660	2.665	2.840664	abcef
3.3525	1.758261	2.54	1.527304	deg
2.04	2.460410	1.7275	2.347617	adef
2.04	2.460410	1.915	2.347617	bdef
1.25875	1.758261	1.665	1.527304	abdeg
4.274375	2.885214	3.665	2.730429	cdefg
1.665	2.183066	1.165	1.910117	acde
1.2275	2.183066	1.54	1.910117	bcde
2.50875	2.885214	2.79	2.730429	abcdefg

Table 8. Parameters for Experiment Two

full 2^5

Parameters			
A nozzle diameter	0.030	0.043	inch
B pressure	45.000	48.000	ksi
C traverse rate	10.000	20.000	in/min
D abrasive flow	0.585	1.170	lb/min
E # passes	2	4	**

GRIT IG80
STANDOFF .150 inch

Table 9a. Sum of Squares Table-Experiment Two

run	entrance depth	effect	SS	
(1)	1.75	5.46875	239.26	
e	3.00	1.62500	21.13	number of passes
c	1.50	-0.96875	7.507813	traverse rate
d	2.00	0.68750	3.781250	abrasive flow rate
abd	2.00	-0.34375	0.945313	
de	4.25	0.34375	0.945313	
ce	2.75	-0.31250	0.781250	
abc	1.50	0.31250	0.781250	
b	2.50	0.25000	0.500000	pressure
ad	2.25	-0.25000	0.500000	
bc	1.00	-0.25000	0.500000	
cde	3.50	-0.21875	0.382813	
bcd	2.00	0.15625	0.195313	
ade	5.00	-0.15625	0.195313	
ace	2.50	-0.12500	0.125000	
abce	3.00	0.09375	0.070313	
a	2.00	0.09375	0.070313	nozzle diameter
abe	4.25	0.09375	0.070313	
acde	3.00	-0.09375	0.070313	
ae	3.50	0.06250	0.031250	
ab	2.50	-0.06250	0.031250	
abde	4.50	-0.06250	0.031250	
abcde	3.25	0.06250	0.031250	
acd	2.00	0.06250	0.031250	
bd	3.00	0.03125	0.007813	
abcd	2.00	0.03125	0.007813	
be	3.50	-0.03125	0.007813	
bce	1.75	-0.03125	0.007813	
ac	1.25	0.03125	0.007813	
bde	5.50	0.00000	0.000000	
bcde	3.50	0.00000	0.000000	
cd	1.50	0.00000	0.000000	

Table 9b. Sum of Squares Table-Experiment Two

run	exit depth	effect	SS	
(1)	2.00	5.10938	208.85	
e	2.50	1.45313	16.89	number of passes
c	1.00	-0.89063	6.345703	traverse rate
d	2.00	0.54688	2.392578	abrasive flow rate
bc	0.75	-0.39063	1.220703	
bce	1.75	-0.35938	1.033203	
b	3.00	0.35938	1.033203	pressure
de	3.50	0.26563	0.564453	
ade	3.75	-0.26563	0.564453	
abc	1.50	0.26563	0.564453	
cde	3.50	-0.23438	0.439453	
acde	3.00	0.23438	0.439453	
abde	4.25	-0.20313	0.330078	
abd	2.25	-0.17188	0.236328	
abcde	3.00	0.17188	0.236328	
ce	2.75	-0.17188	0.236328	
ad	2.25	-0.17188	0.236328	
cd	1.50	0.17188	0.236328	
be	3.50	0.14063	0.158203	
ace	2.25	-0.14063	0.158203	
bcd	2.00	0.10938	0.095703	
bcde	3.00	-0.10938	0.095703	
abe	4.50	0.10938	0.095703	
abce	2.75	0.10938	0.095703	
a	2.00	0.07813	0.048828	nozzle diameter
ac	1.25	0.07813	0.048828	
abcd	2.00	-0.04688	0.017578	
acd	1.75	-0.04688	0.017578	
ae	3.00	-0.01563	0.001953	
bde	5.50	0.01563	0.001953	
bd	2.00	-0.01563	0.001953	
ab	2.00	0.01563	0.001953	

Table 10. Regression Results-Experiment Two

Regression Output:ENTRANCE DEPTH

Constant	-3.42
Std Err of Y Est	0.47
R Squared	0.85
No. of Observations	32
Degrees of Freedom	26

	diameter	pressure	traverse	flow	passes
X Coefficient(s)	7.21	0.08	-0.10	1.18	0.81
Std Err of Coef	12.80	0.06	0.02	0.28	0.08

Regression Output:EXIT DEPTH

Constant	-4.90
Std Err of Y Est	0.52
R Squared	0.79
No. of Observations	32
Degrees of Freedom	26

	diameter	pressure	traverse	flow	passes
X Coefficient(s)	6.01	0.12	-0.09	0.93	0.73
Std Err of Coef	14.24	0.06	0.02	0.32	0.09

Table 11. Depth of Cut - Experiment Two

	Entrance Depth		Exit Depth	
	Predicted	Experiment	Predicted	Experiment
Run	$\hat{z}_1$	z_1	$\hat{z}_2$	z_2
(1)	1.89	1.75	1.78	2.00
d	1.98	2.00	1.86	2.00
b	2.14	2.50	2.14	3.00
ab	2.23	2.50	2.22	2.00
c	0.92	1.50	0.89	1.00
ac	1.02	1.25	0.97	1.25
bc	1.17	1.00	1.25	0.75
abc	1.27	1.50	1.33	1.50
bcd	2.58	2.00	2.33	2.00
ad	2.67	2.25	2.41	2.25
bd	2.83	3.00	2.69	2.00
abd	2.92	2.00	2.77	2.25
cd	1.61	1.50	1.44	1.50
acd	1.70	2.00	1.52	1.75
a	1.86	2.00	1.80	2.00
abcd	1.95	2.00	1.88	2.00
e	3.52	3.00	3.23	2.50
ae	3.61	3.50	3.31	3.00
be	3.77	3.50	3.59	3.50
abe	3.86	4.25	3.67	4.50
ce	2.55	2.75	2.34	2.75
ace	2.64	2.50	2.42	2.25
bce	2.80	1.75	2.70	1.75
abce	2.89	3.00	2.78	2.75
de	4.20	4.25	3.78	3.50
ade	4.30	5.00	3.86	3.75
bde	4.45	5.50	4.14	5.50
abde	4.55	4.50	4.22	4.25
cde	3.23	3.50	2.89	3.50
acde	3.33	3.00	2.97	3.00
bcde	3.48	3.50	3.25	3.00
abcde	3.58	3.25	3.33	3.00

Table 12. Parameters for Experiment Three

full 2^5

	Parameters	low	high	
A	nozzle diameter	0.03	0.063	inch
B	grit type	G120	IG80	
C	pressure	30	48	ksi
D	traverse rate	10	20	in/min
E	abrasive flow rate	0.6	1.2	lb/mingarnet
		0.585	1.17	lb/miniron grit

Table 13. Sum of Squares Table - Experiment Three

Number of passes required to cut completely through slab

run	passes	effect	sum of squares
(1)	19	32.0625	8224.031
e	8	-7.5625	457.5312
d	38	7.1875	413.2812
c	12	5.9375	282.0312
bcd	20	3.4375	94.53125
a	15	3.3125	87.78125
bd	24	-2.5625	52.53125
bce	5	-2.5625	52.53125
ace	7	-2.5625	52.53125
bc	9	2.3125	42.78125
abd	91	-2.0625	34.03125
ac	31	2.0625	34.03125
ab	12	1.5625	19.53125
acd	32	1.4375	16.53125
cd	21	-1.3125	13.78125
abde	81	1.3125	13.78125
abcde	71	1.3125	13.78125
be	11	1.1875	11.28125
de	71	-1.1875	11.28125
ade	32	1.0625	9.03125
cde	01	1.0625	9.03125
ae	01	0.9375	7.03125
bcde	9	-0.6875	3.78125
abce	8	0.6875	3.78125
bde	51	0.5625	2.53125
acde	31	-0.4375	1.53125
ad	23	-0.3125	0.78125
abe	91	-0.3125	0.78125
abcd	42	0.1875	0.28125
ce	6	0.1875	0.28125
b	51	-0.1875	0.28125
abc	12	-0.1875	0.28125

Table 14. Parameters for Experiment Four

Parameters		Response
grit type	G120 and IG80	number of passes to cut through from top and bottom
pressure	48 ksi	
traverse	10 in/min	
flow rate	1.2 lb/min	
standoff	.150 inch	
nozzle	.030 inch	

Table 15. Parameters for Experiment Five

full 3^3

Parameters

Pressure	30	40	48	ksi
Flow	0.6	0.9	1.2	lb/min
Passes	2	4	6	**

nozzle diameter	.030 inch
grit	G120
traverse	10 inch/min
standoff	.150 inch

Table 16a. Sum of Squares - Experiment Five

A Pressure
B Abrasive Flow Rate
C Number of Passes

effect	SS	entrance depth
-	477.120	2.00
C(l)	34.722	2.50
A(l)	9.031	2.25
B(l)	4.014	2.25
C(q)	0.782	4.00
B(q)	0.782	2.25
AC(lq)	0.563	5.00
BC(lq)	0.340	5.00
BC(ll)	0.188	4.00
A(q)	0.140	2.75
ABC(lqq)	0.125	6.25
AC(qq)	0.113	5.50
AC(ql)	0.111	4.75
AC(ll)	0.083	3.75
ABC(qlq)	0.056	6.25
AB(ql)	0.043	3.50
ABC(lql)	0.042	5.00
ABC(lll)	0.031	4.50
ABC(qqq)	0.029	6.25
AB(lq)	0.016	3.00
AB(qq)	0.014	3.25
ABC(llq)	0.010	6.00
BC(ql)	0.007	4.00
AB(ll)	0.005	3.00
ABC(qql)	0.003	6.00
BC(qq)	0.002	5.00
ABC(qll)	0.000	5.50

Table 16b. Sum of Squares - Experiment Five

A Pressure
B Abrasive Flow Rate
C Number of Passes

SS	effect	exit depth
462.52	-	2.00
10.13	BC(11)	4.00
2.81	ABC(111)	5.00
2.06	C(q)	4.50
1.69	B(q)	2.25
1.32	A(l)	2.25
0.72	AB(1q)	3.00
0.68	AC(1q)	5.00
0.67	BC(qq)	5.00
0.58	AC(ql)	4.75
0.34	ABC(lqq)	6.25
0.23	ABC(qql)	6.00
0.14	ABC(qqq)	6.25
0.02	AB(qq)	3.25
0.02	AC(qq)	5.75
-0.02	ABC(qlq)	6.25
-0.17	AB(ql)	2.50
-0.37	A(q)	2.75
-0.56	ABC(lql)	4.50
-0.56	ABC(qll)	5.50
-1.06	ABC(llq)	5.50
-2.29	BC(ql)	4.00
-2.50	AB(ll)	3.00
-2.54	BC(lq)	4.00
-2.63	AC(ll)	3.75
-6.46	B(l)	2.25
-6.58	C(l)	2.50

Table 17. Regression Results - Experiment Five

Regression Output: Entrance Depth

Constant		-3.09836	
Std Err of Y Est		0.383349	
R Squared		0.934054	
No. of Observations		27	
Degrees of Freedom		23	
	pressure	flow	passes
X Coefficient(s)	0.079007	1.574074	0.694444
Std Err of Coef.	0.010019	0.301187	0.045178

Regression Output: Exit Depth

Constant		-2.92440	
Std Err of Y Est		0.467511	
R Squared		0.903635	
No. of Observations		27	
Degrees of Freedom		23	
	pressure	flow	passes
X Coefficient(s)	0.077527	1.342592	0.701388
Std Err of Coef.	0.012218	0.367311	0.055096

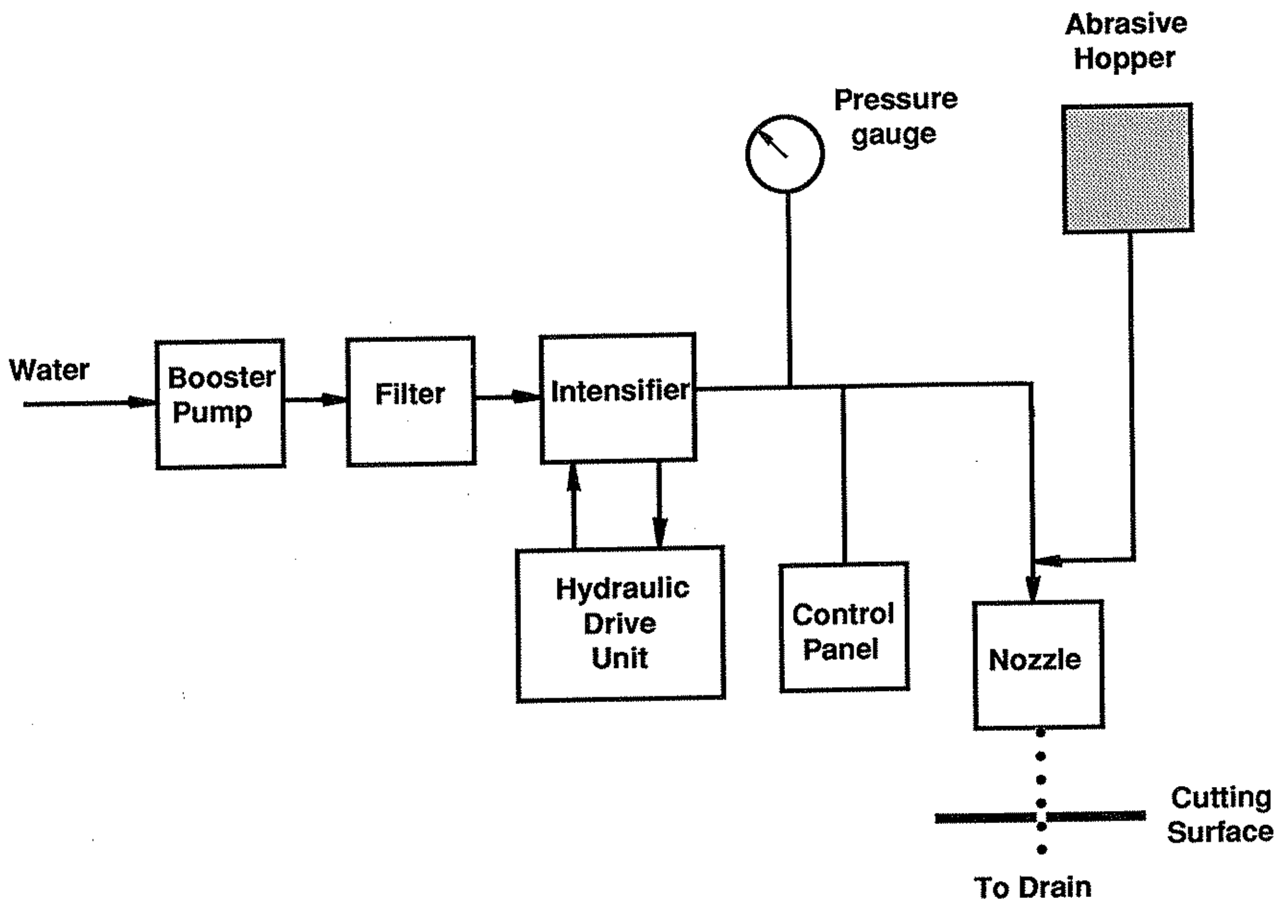

Figure 1. Basic Waterjet System

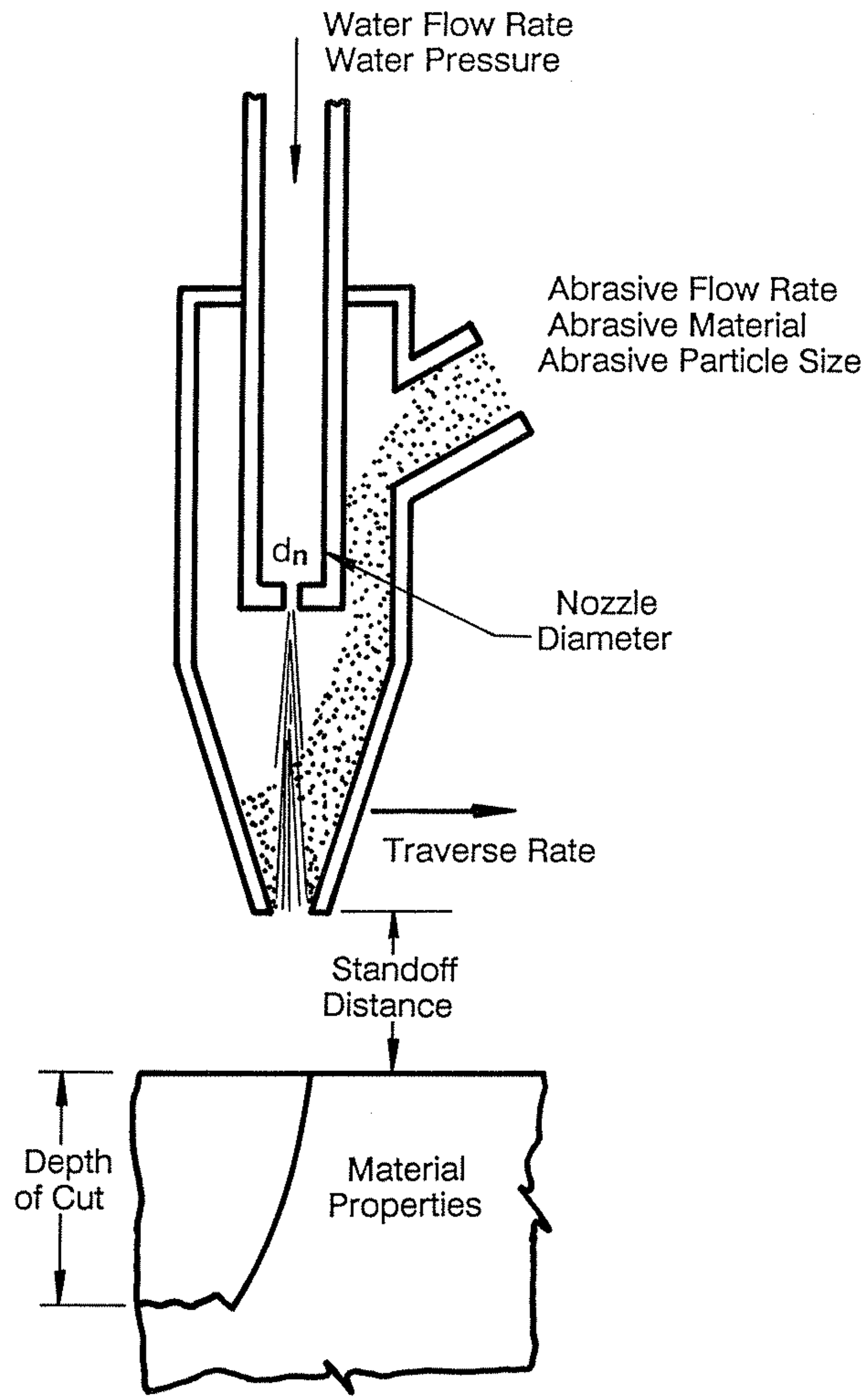

Figure 2. Typical Nozzle

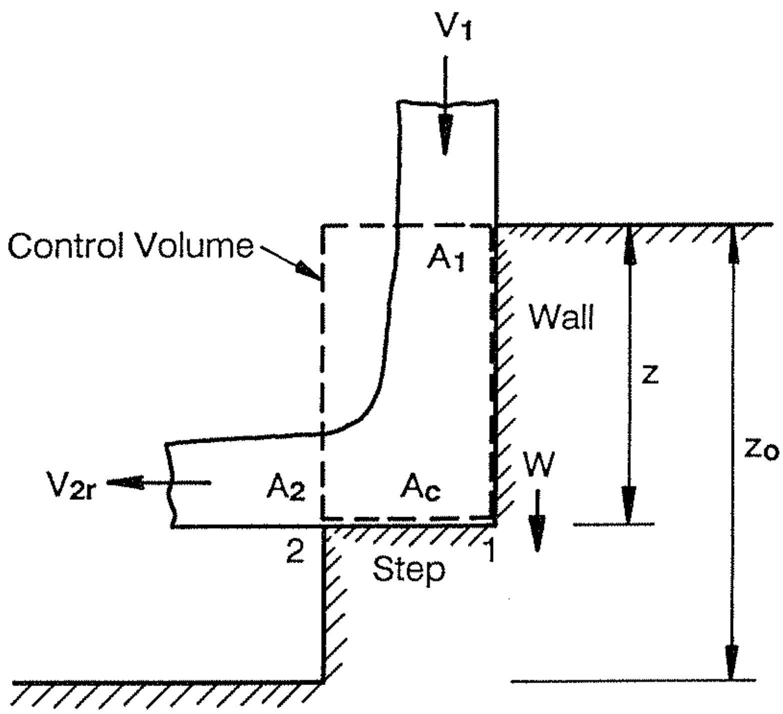

Figure 3. Control Volume

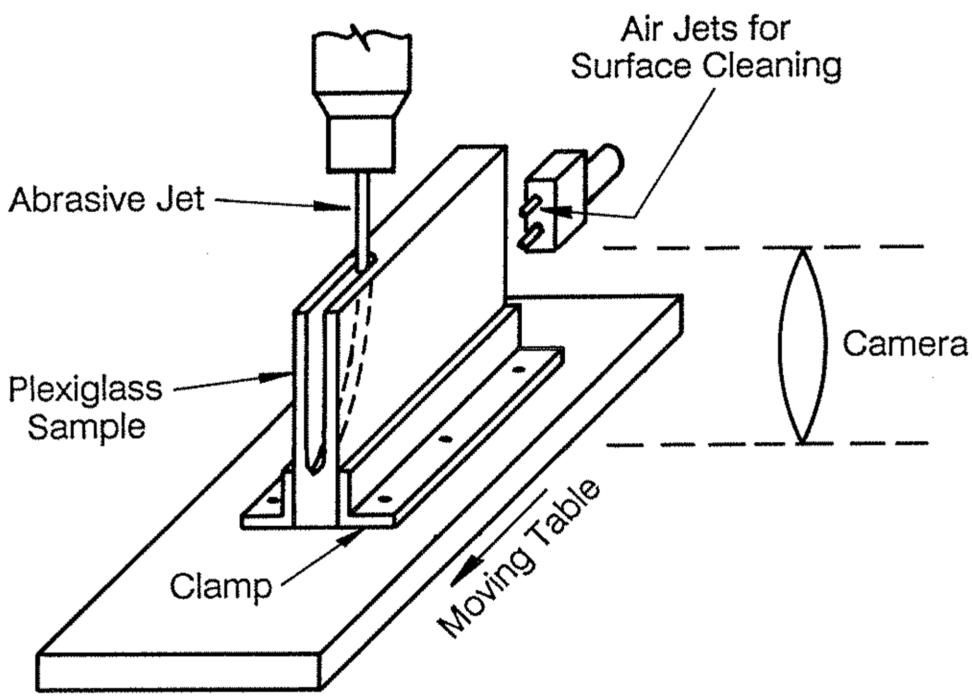

Figure 4. Model of Waterjet Cutting Process

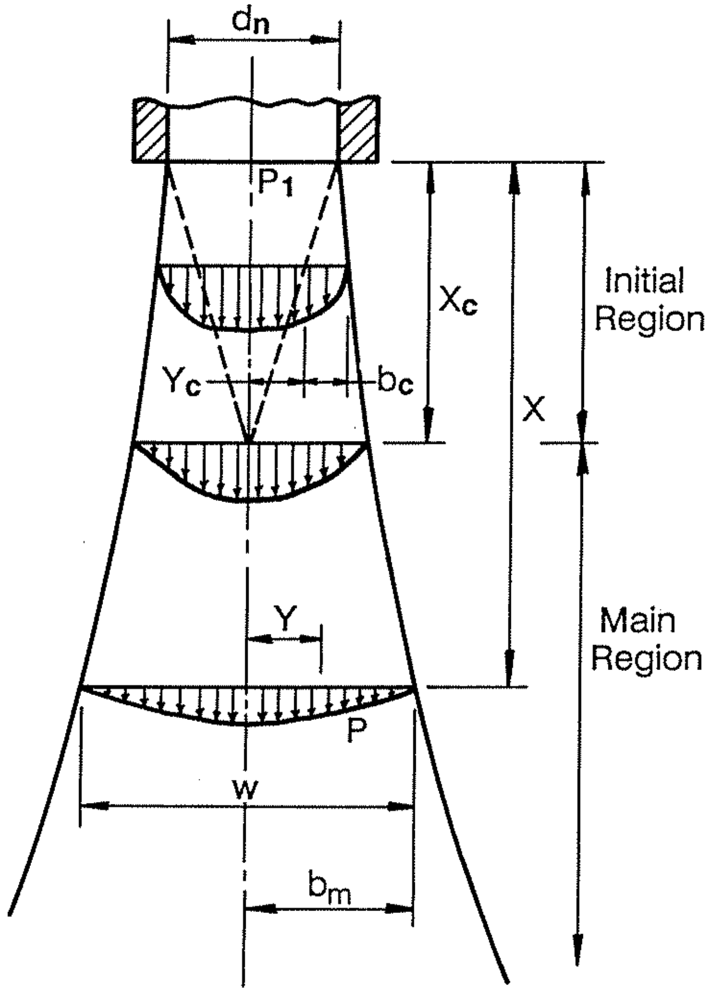

Figure 5. Jet Spread

LABELING OF SAMPLES

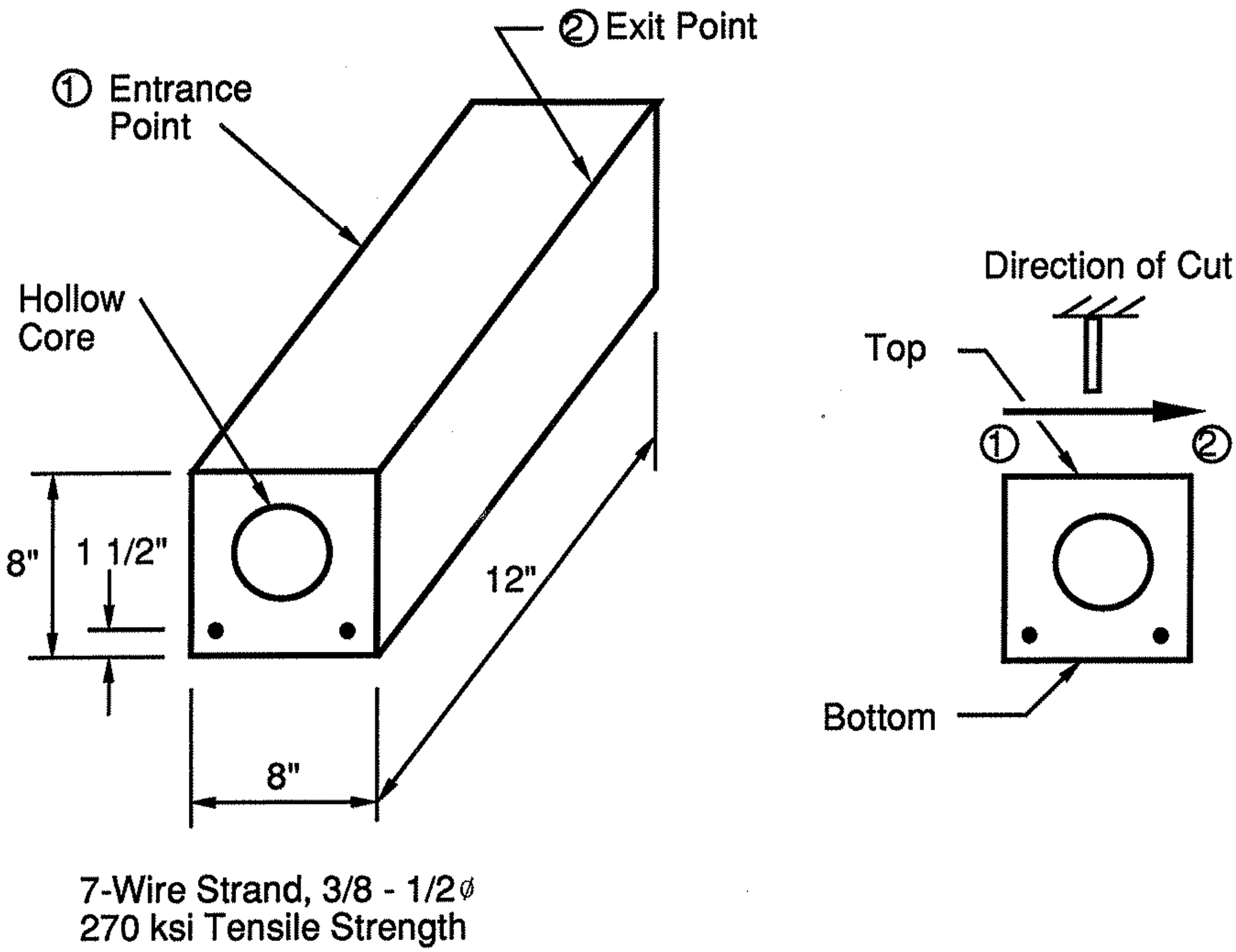

Figure 6. Concrete Samples

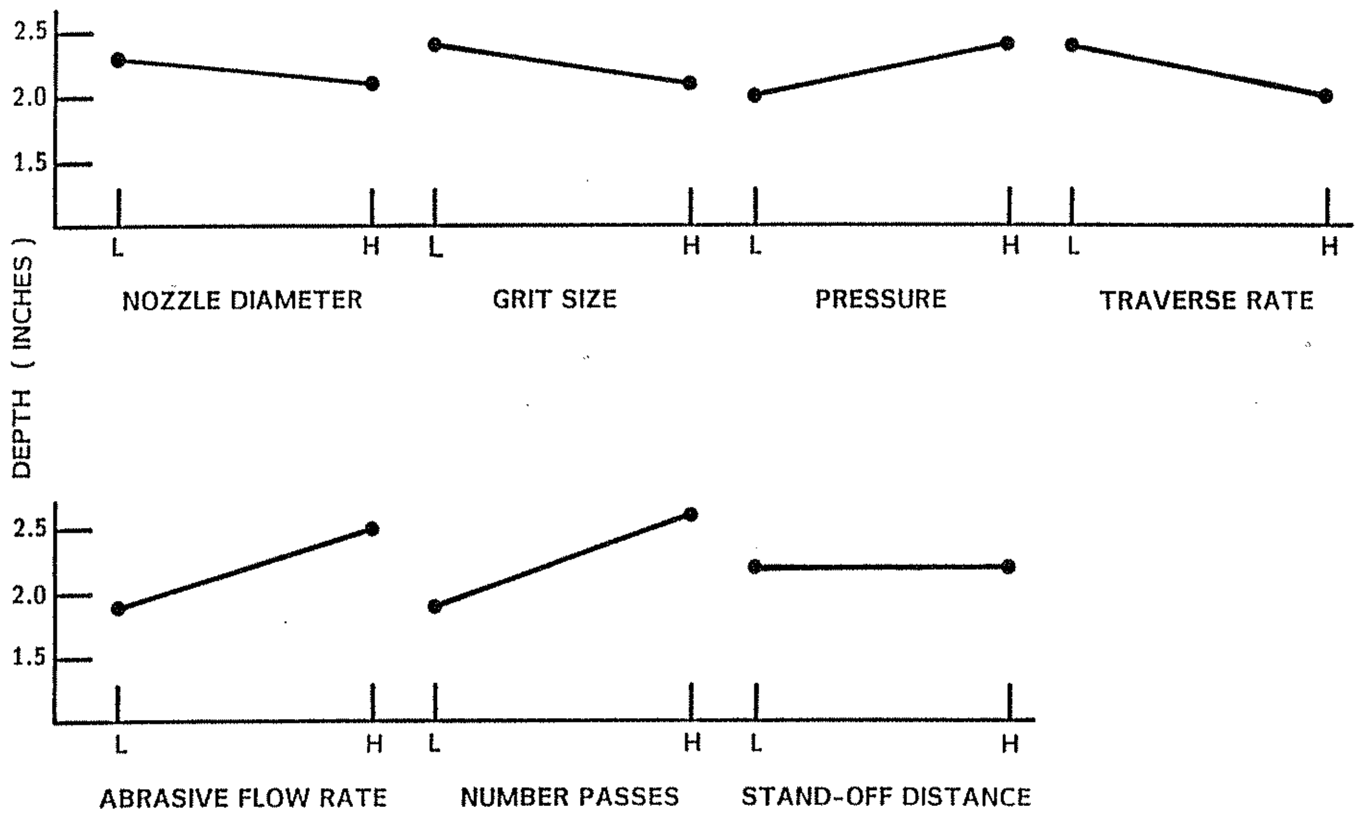

Figure 7. Parameter Effects - Experiment One

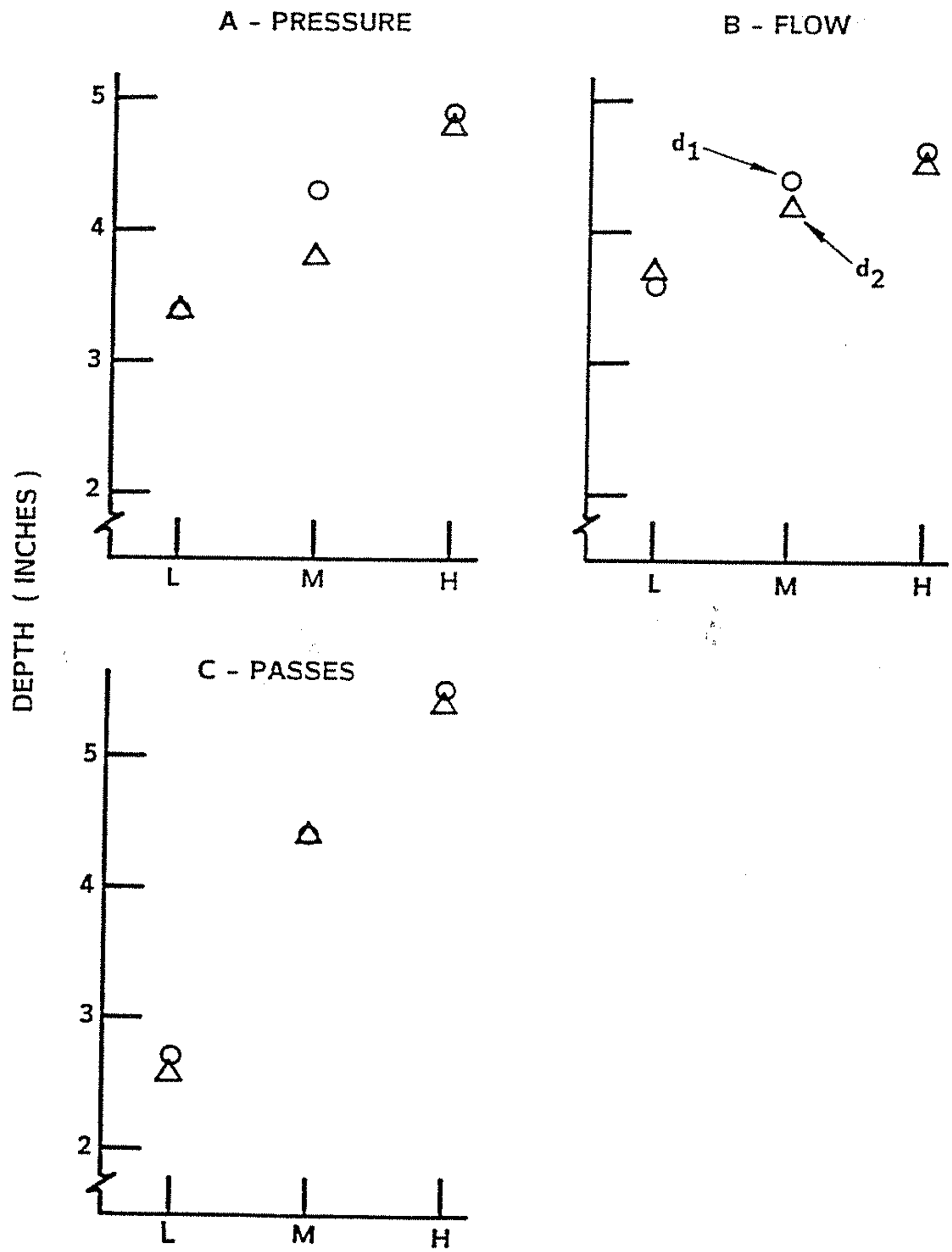

Figure 8. Parameter Effects - Experiment Five

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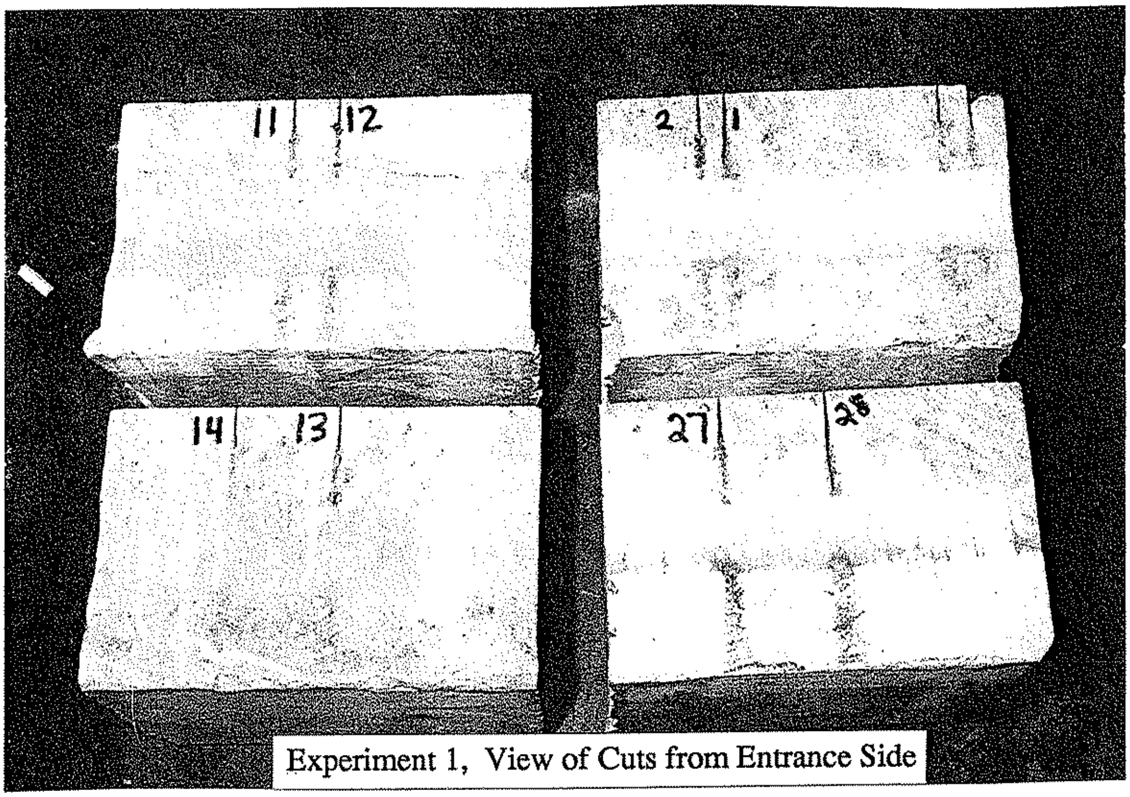
Appendix A. Photographs

Photographs of some representative concrete blocks appear on the following pages. These blocks demonstrate the effects of the various parameters on depth of cut and kerf quality. The cuts depicted are as follows.

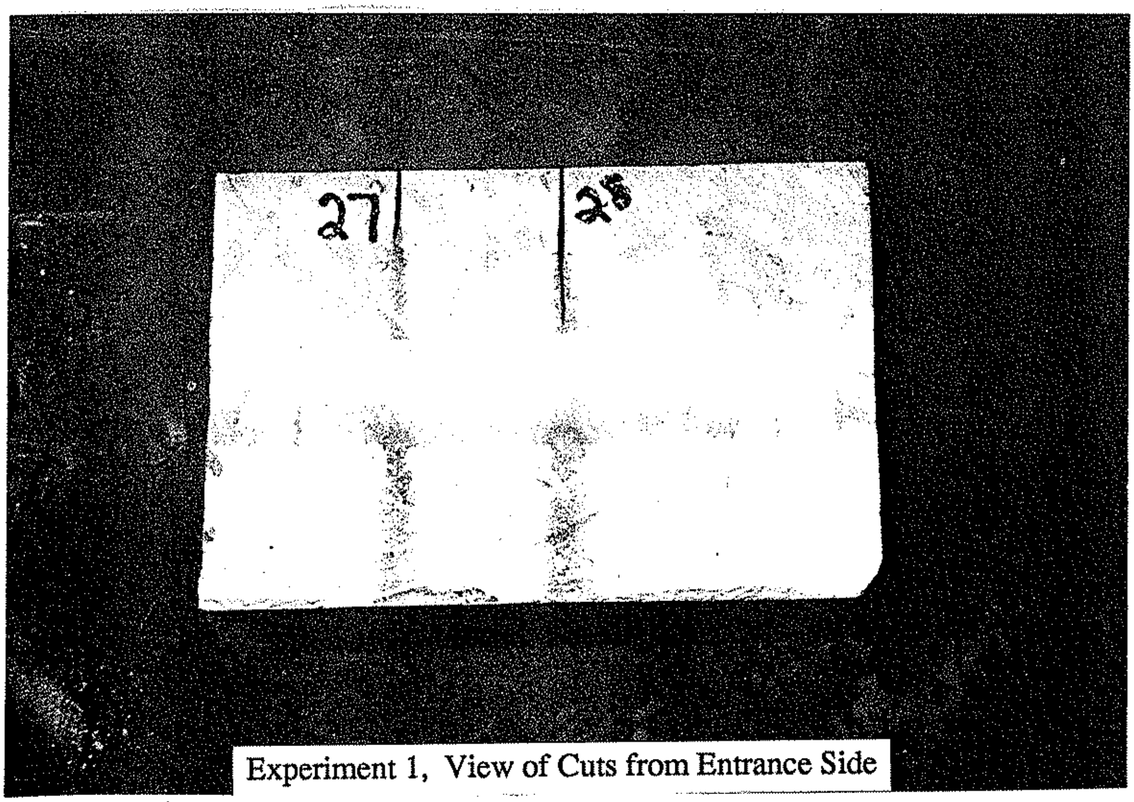
Photograph Number	Experiment	View of Cuts
1- 2	1	1,2,11,12,13,14,27,28 from entrance side
3	2	1-32 from entrance side
4-5	3	9,10,15,16 from bottom view
6	3	9,10,15,16 from entrance side
7	3	9,10,15,16 from exit side
8-9	4	iron grit cut on the left garnet cut on the right
10	5	1-4,21-24 from bottom
11	5	1-4,21-24 from entrance
12	5	1-4,21-24 from exit

Appendix A. Photographs



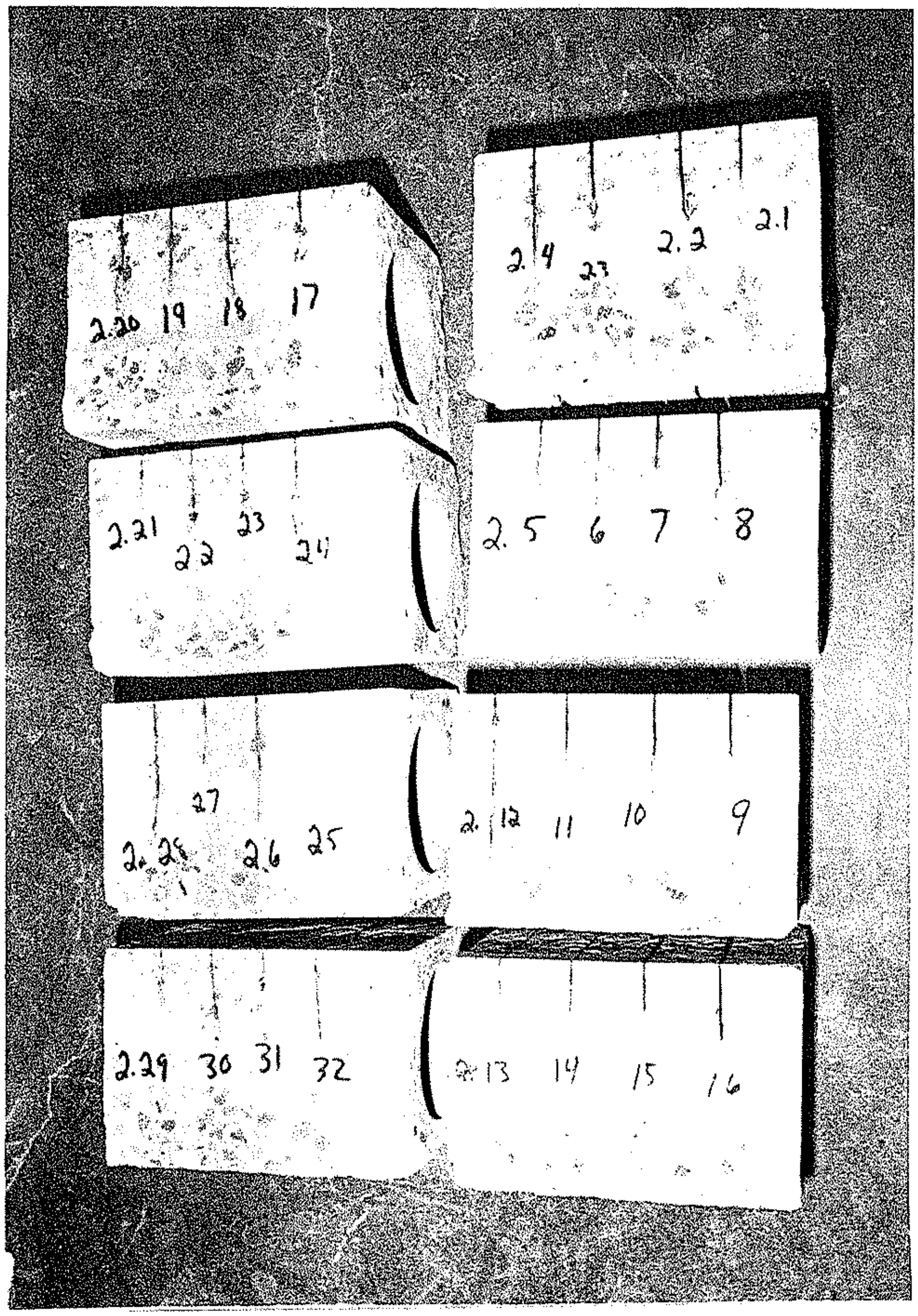
Experiment 1, View of Cuts from Entrance Side

Photograph #1



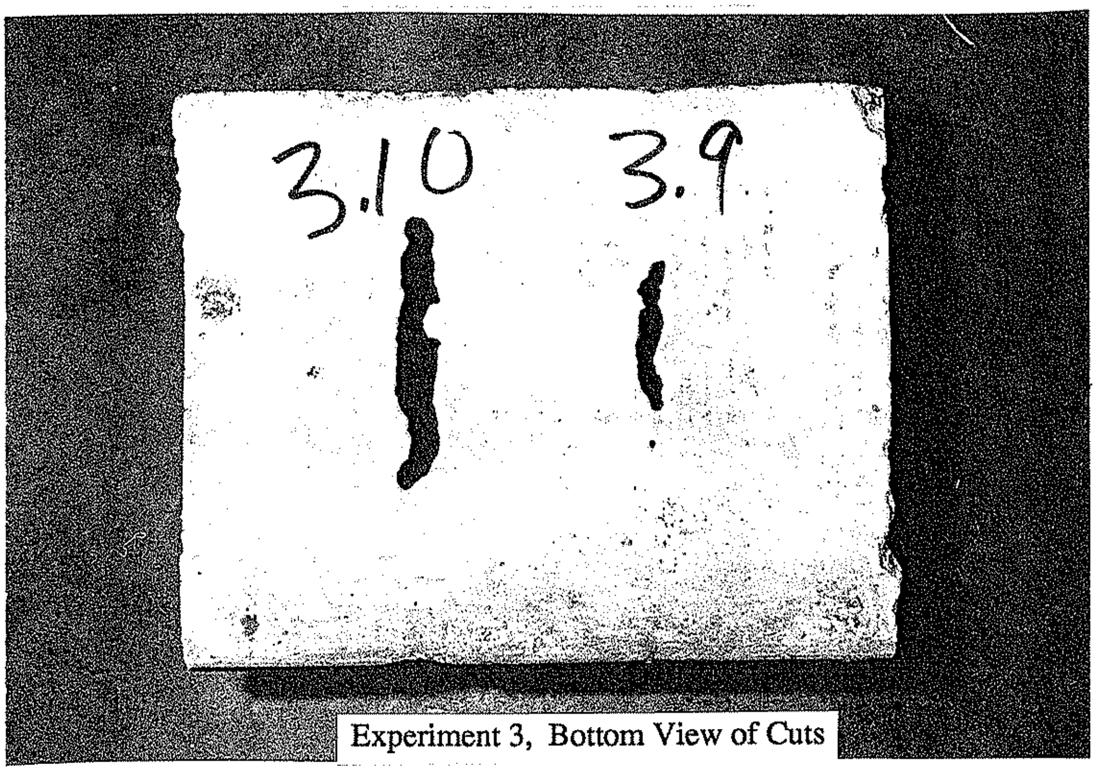
Experiment 1, View of Cuts from Entrance Side

Photograph #2



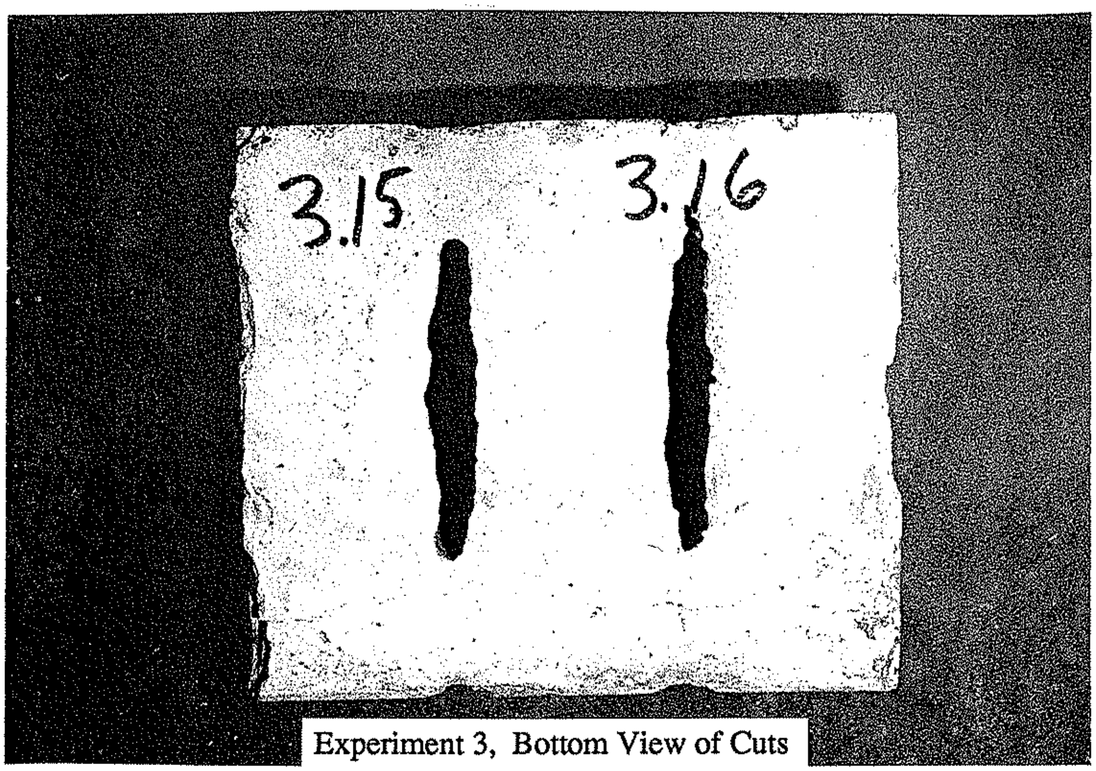
Experiment 2, View of Cuts from Entrance Side

Photograph #3



Experiment 3, Bottom View of Cuts

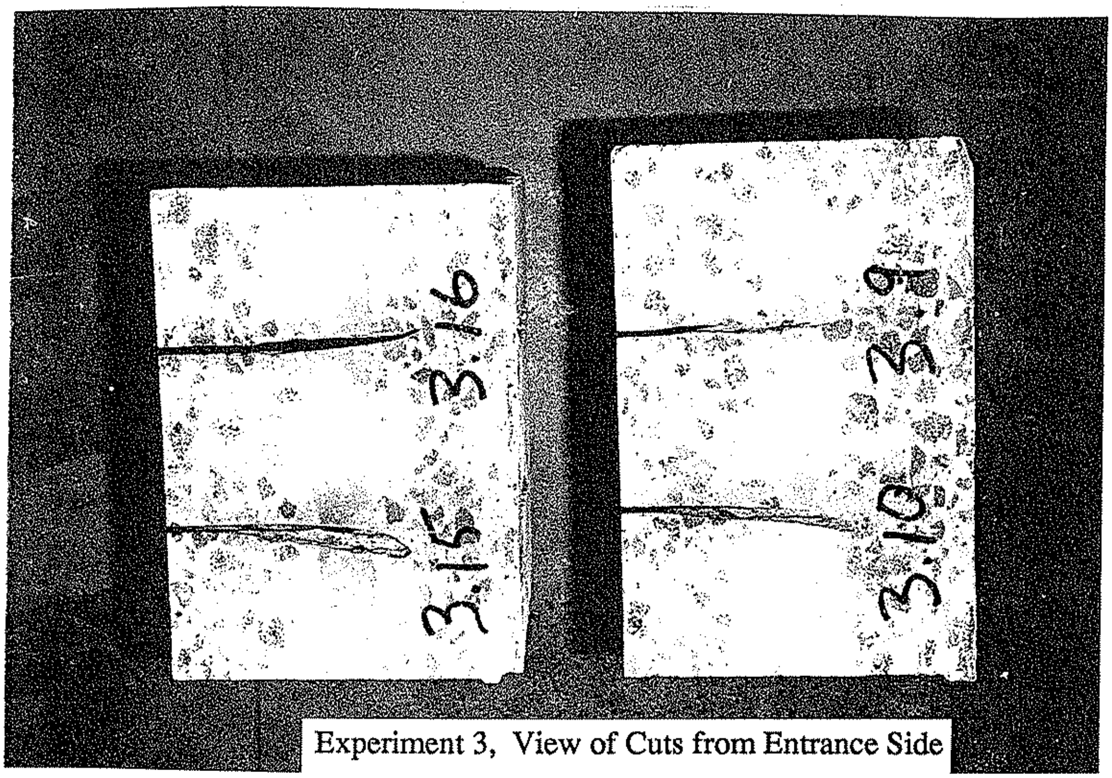
Photograph #4



Experiment 3, Bottom View of Cuts

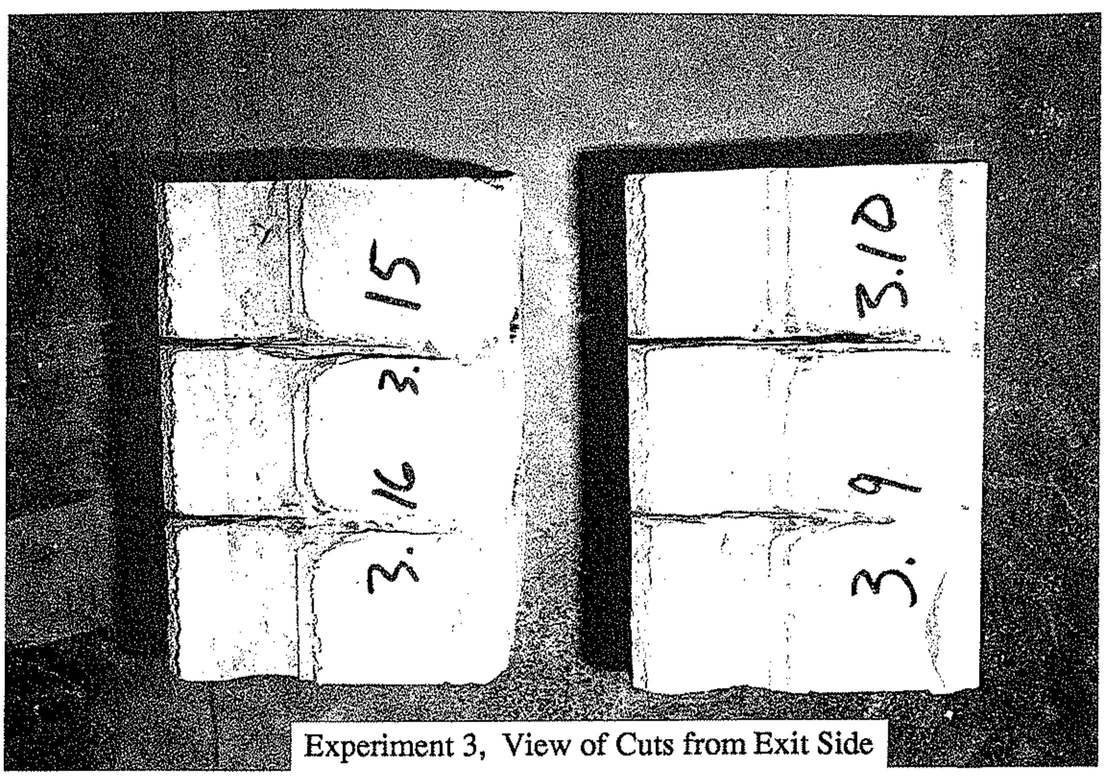
Photograph #5

Appendix A. Photographs



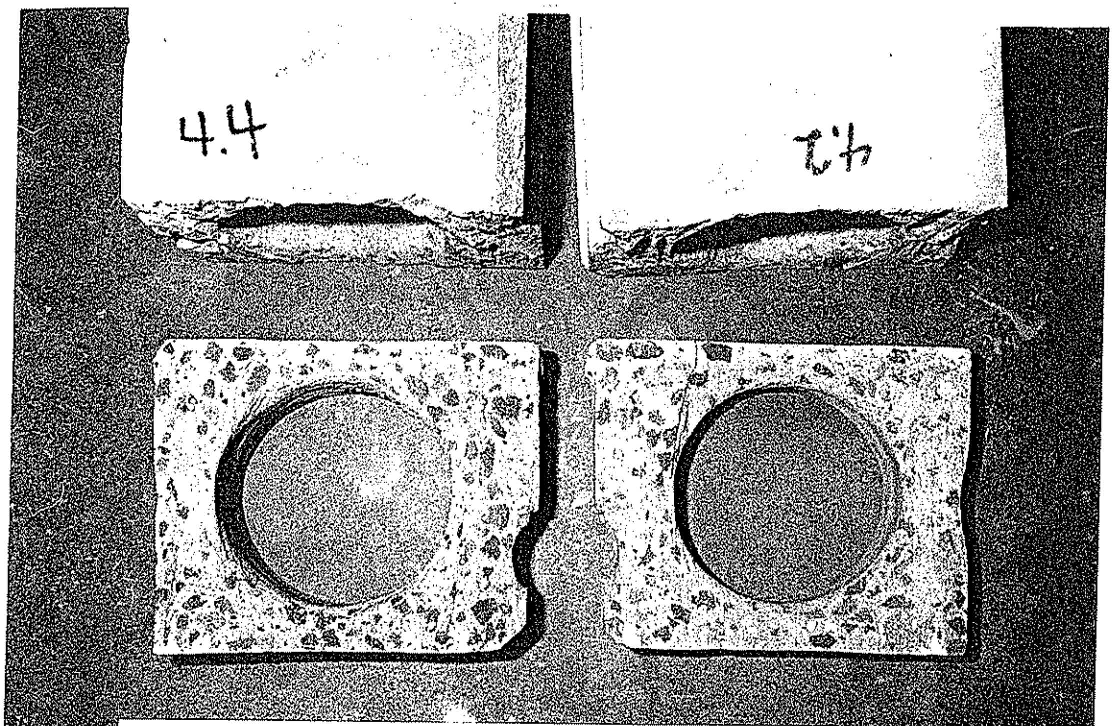
Experiment 3, View of Cuts from Entrance Side

Photograph #6



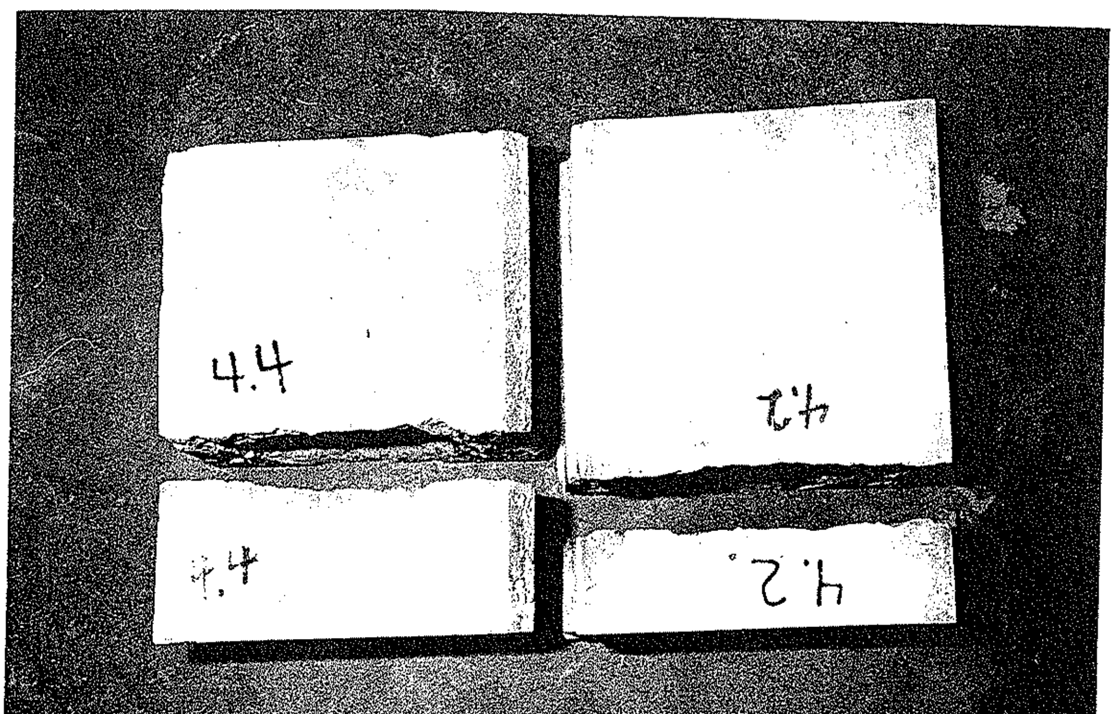
Experiment 3, View of Cuts from Exit Side

Photograph #7



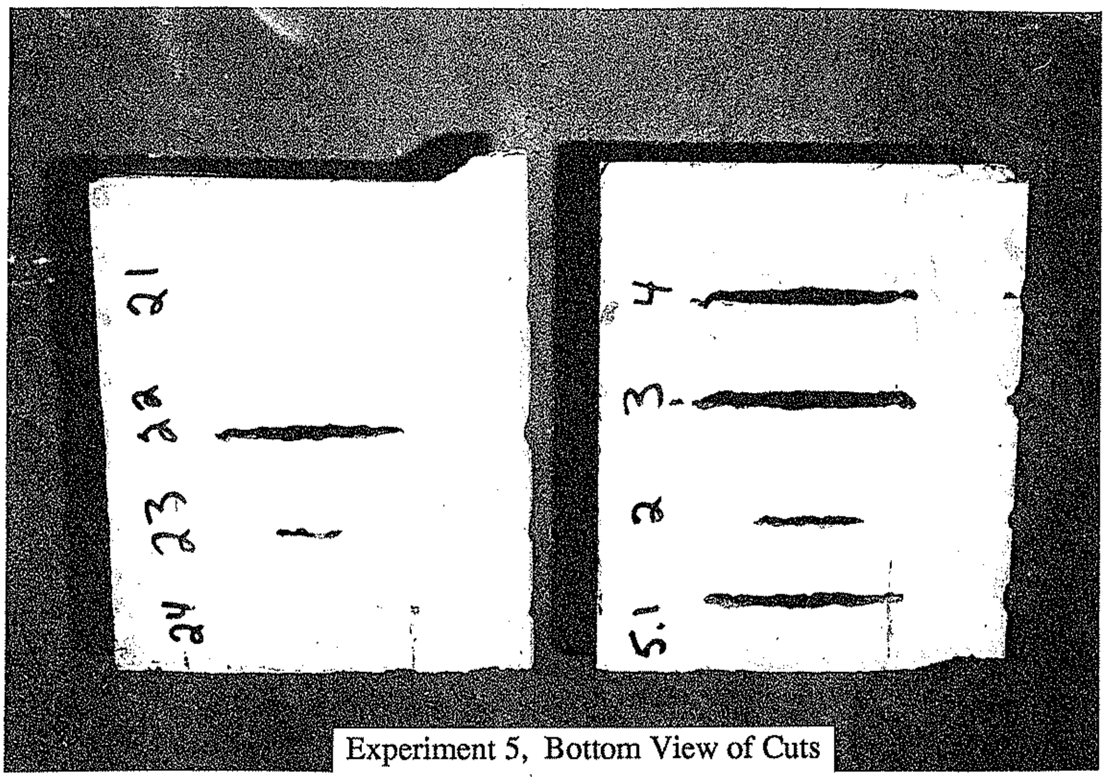
Experiment 4, Iron Grit Cut on Left, Garnet Grit Cut on Right

Photograph #8



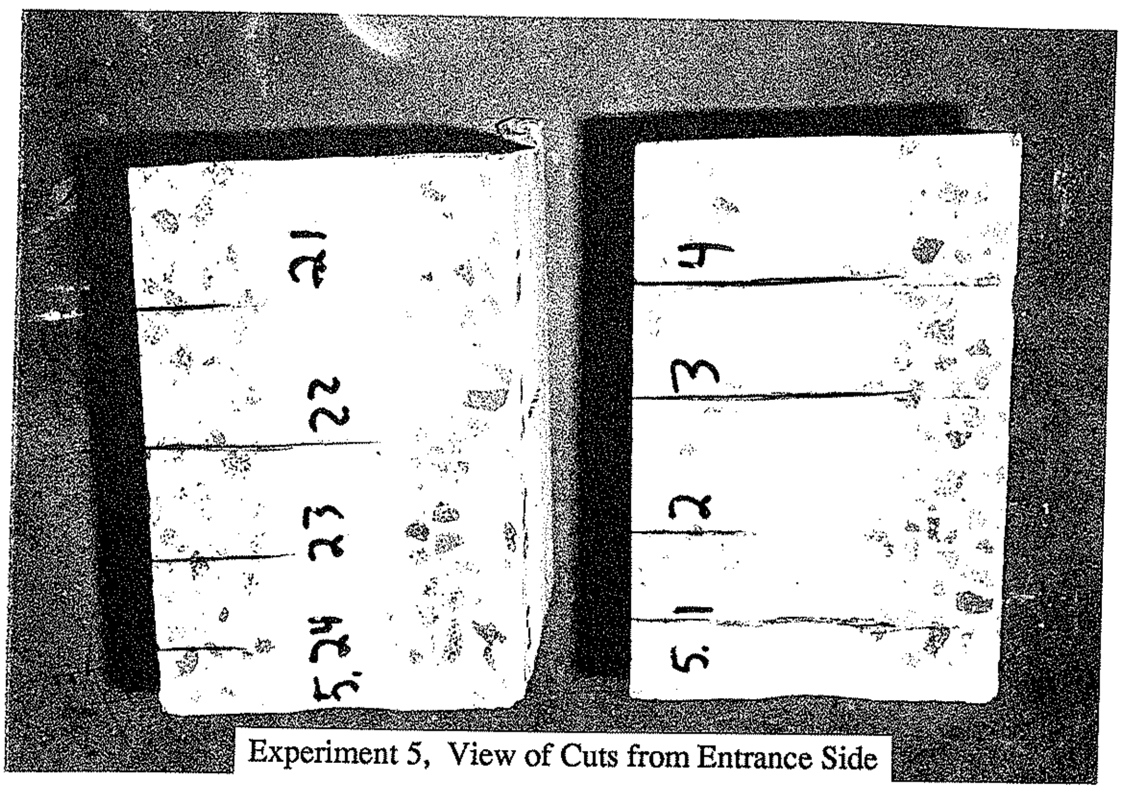
Experiment 4, Iron Grit Cut on Left, Garnet Grit Cut on Right

Photograph #9



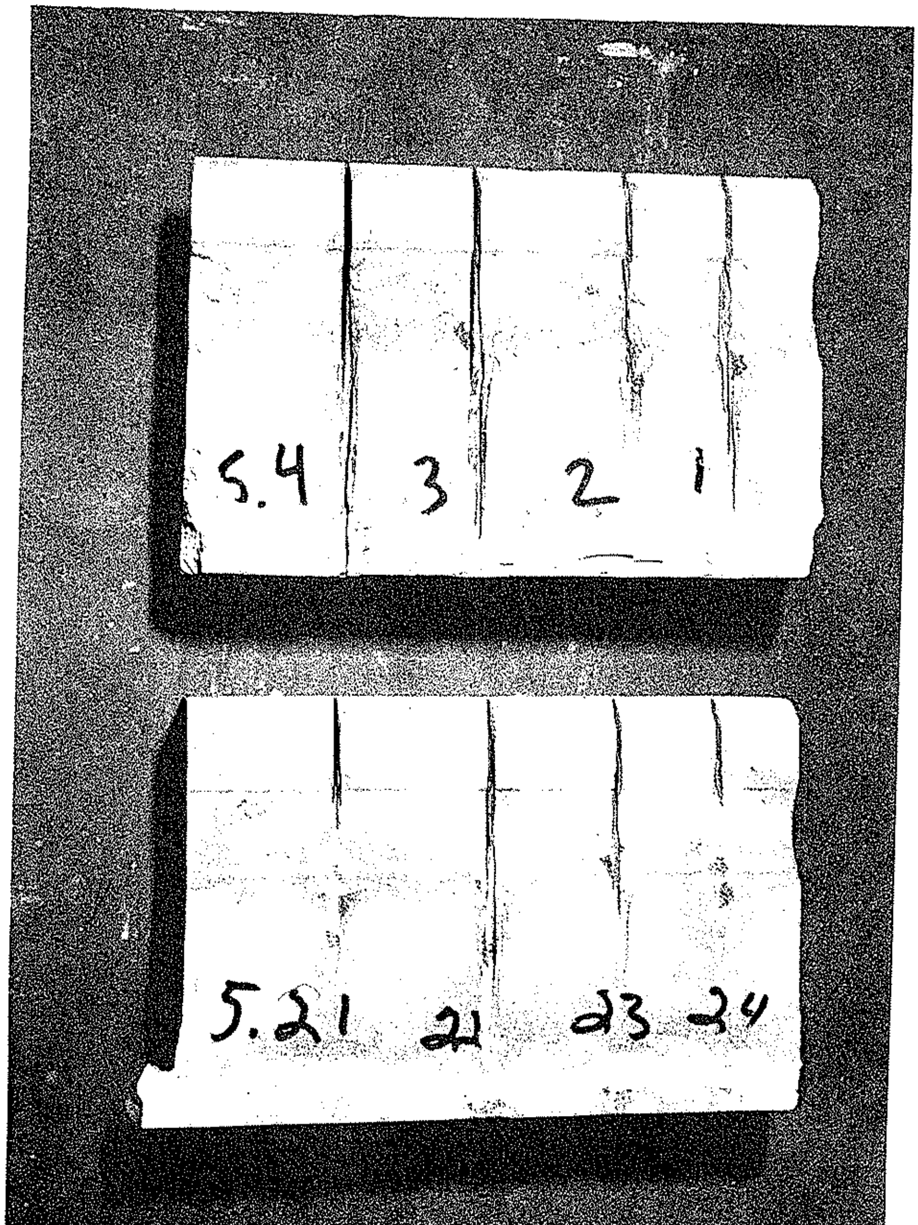
Experiment 5, Bottom View of Cuts

Photograph #10



Experiment 5, View of Cuts from Entrance Side

Photograph #11



Experiment 5, View of Cuts from Exit Side

Photograph #12